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Gran Telescopio de Canarias, S.A.

Instituto de Astrofísica de Canarias
Vía Láctea s/n
38200 - LA LAGUNA, TENERIFE, Islas Canarias
Tfno +34 922 315 031 Fax +34 922 315 032

Centro Común de Astrofísica de La Palma
Cuesta de San José s/n
38712 BREÑA BAJA, LA PALMA, Islas Canarias
Tfno +34 922 425 720 Fax +34 922 425 701

http://www.gtc.iac.es   E-Mail: gtc@iac.es

Received by	Pedro Alvarez Project Director	Signed in the original copy
Authorized by	Pedro Alvarez Project Director **Date:**	Signed in the original copy **28/08/08**

Report of the Gran Telescopio Canarias Future Instrumentation Working Group

Stephen Eikenberry (Chair)
Santiago Arribas
Jesús González
Artemio Herrero
René Rutten

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Executive Summary

The primary purpose of this report is to provide guidance to the Project Office and offer a basis for future discussion within the scientific user community of the Gran Telescopio Canarias (GTC) regarding priorities for future instrumentation. The GTC Project Office commissioned the Future Instrumentation Working Group to investigate instrument complements needed in the future in order to optimize the scientific productivity of the GTC, in the context of the scientific drivers from the GTC community, observing capabilities available to the community, and competing capabilities around the world. The Working Group subdivided the "future" into: the "Near-Future" (priorities from the current era to 2013 or beyond), the "Mid-Future" (priorities for 2018 and beyond), and the "Far Future" (2023 and beyond). The Working Group expects that a similar process to review, re-assess, and re-establish priorities should take place approximately every 5 years (or more frequently if the community so determines).

For the Near-Future term, the key recommendations of this Working Group are the following:

1. GTC should develop a medium-resolution (R > 10,000) optical multi-object spectrograph for on-sky commissioning in 2013. The estimated total cost of this project is 8-10 million Euros (including manpower).
2. GTC should develop a medium-resolution (R > 10,000) near-infrared multi-object spectrograph for on-sky commissioning in 2013. The estimated total cost of this project is 8-10 million Euros (including manpower).
3. Queue-scheduled observations will be critical to optimizing the scientific return of the GTC, and should be fully supported.
4. Visitor or "PI" instruments provide an important contribution to the potential scientific flexibility and productivity of the GTC, and the GTC should develop clear guidelines for working with such instruments.
5. The high-resolution portion of the proposed SIDE instrument would seem to fulfill the requirements for the medium-resolution optical spectrograph. The low-resolution and infrared portions of the SIDE instrument would not seem to contribute directly to the merit criteria we have established here.
6. GTC should commission a study as soon as possible to assess the suitability of the UES instrument for meeting the scientific needs of the GTC community in the area of high-resolution optical spectroscopy, as well as possible alternative plans for this capability.

For the Mid-Future term, the key recommendations of this Working Group are the following:

7. GTC should promote the development of science cases from the community and initiate feasibility studies for Multi-Conjugate Adaptive Optics capabilities, and related instrumentation capabilities, beginning no later than early 2010.
8. GTC should promote the development of science cases from the community and initiate feasibility studies for Ground Layer Adaptive Optics capabilities, and related instrumentation capabilities, beginning no later than early 2010. Because GLAO performance is closely tied to ground layer turbulence scale height at ORM, GTC should commission a study to provide high-resolution measurements of the ground layer properties in 2009.
9. GTC should expect to develop additional instrumentation capabilities over this term. The details of the critical scientific performance characteristics of such instruments will emerge over the next few years in terms of both scientific and technological advances.

Finally, in the Far-Future term, GTC will need to be open to fundamentally re-assessing its direction and mission in a time of multiple ground-based ELTs and a mature JWST space-based facility.

I. Introduction/Motivation

A. Scope of This Report

The primary purpose of this report is to provide guidance to the Project Office and offer a basis for future discussion within the scientific user community of the Gran Telescopio Canarias regarding priorities for future instrumentation. The GTC Project Office commissioned the Future Instrumentation Working Group to investigate instrument complements needed in the future in order to optimize the scientific productivity of the GTC, in the context of: (a) the scientific drivers from the GTC community; (b) observing capabilities available to the community; (c) competing capabilities around the world. The Working Group subdivided the "future", for the purposes of this report, into three separate time ranges: the "Near-Future" (encompassing priorities for capabilities from the current moment to those which should come on line in 2013 or beyond), the "Mid-Future" (encompassing priorities for capabilities which should come on line in 2018 and beyond), and the "Far Future" (encompassing priorities for capabilities which should come on line in 2023 and beyond). The Working Group expects that a similar process to review, re-assess, and re-establish priorities should take place approximately every 5 years after iteration based on community interests (or more frequently, if desired).

The fundamental mindset of the Working Group was to take the interests of the full range of the GTC partnership to heart. We acknowledge that a full determination of detailed priorities for and specifications of instrumentation clearly requires the participation of a broader swath of the GTC community than can possibly interact properly in a small committee environment such as this. In addition, we note that the GTC is multi-national, and no specific "national strategic plan" for astronomy was available to help define/guide our efforts. For similar reasons, the Working Group did not have access to any well—defined statement of expected funding levels or even funding sources for future instrumentation for GTC.

Accordingly, rather than attempt to define particulars of instrument selection and specifications, we instead chose to focus our energies on investigating and refining broad areas and directions for future GTC instrument development. Determination of specific instrument requirements and features will require further study and definition by GTC scientific community and, together with feedback on constraints of available funding, balanced to provide the optimal scientific return for the observatory as a whole.

In the remainder of this section, we review the necessary background and contextual information needed to begin consideration of the future instrumentation priorities of the GTC. In Section II, we present considerations for instrumentation priorities in the Near-Future (2013+) term. In Section III, we present considerations for instrumentation priorities in the Mid-Future (2018+) term. Finally, in Section IV, we present a brief discussion of likely considerations for GTC instrumentation in the Far-Future (2023+) term.

B. Background/Context Information

As noted above, key issues for determining the optimal set of future instrument priorities on the GTC are the current observing capabilities available to the GTC community, as well as the current and envisioned competing capabilities around the world. In Subsection I.B.1 below, we provide a brief review of the GTC instrumentation suite currently under development which we take as the "existing baseline" capabilities. In Subsection I.B.2, we present a listing of current observatories and/or surveys available for use in a broader worldwide-community sense – a detailed summary of the capabilities of each is well beyond the scope of this report, but this list should provide some indication of the facilities we considered during the preparation of this report. In Subsection I.B.3, we present a similar list of future observatories which will be part of the GTC scientific context in the coming decade.

1. "Current" GTC Instruments

We begin with a brief review of "current" instrumentation for the GTC, as defined by the GTC Project Office. We note that for consistency's sake this list includes only the instruments which have been approved for construction and installation on the GTC at the time of this report.

a. OSIRIS

OSIRIS is a powerful multi-purpose workhorse instrument for the GTC operating in the optical waveband (0.36-1.0 µm). OSIRIS was specifically designed for narrow-band tunable-filter imaging, -- a uniquely competitive general-science niche among 8m to 10m-class telescopes. OSIRIS also provides a very full set of other observational modes, including long-slit and multi-object spectroscopy (R<~ 5000), fast photometry and spectroscopy, as well as powerful CCD-transfer/telescope-nodding/tunable-filter combination modes. It covers a significant portion of the unvignetted GTC field of view with a proper oversampling of good seeing ORM conditions. Narrow-band imaging can be continuously tuned from 365 to 1000 nm (FWHM from 12 to 40 Å). Spectroscopically, it samples R = $\lambda/\Delta\lambda$ resolutions from 300 to ~5000 (0.6" slit width), and in MOS mode can accommodate from 40 to several hundred object spectra in fields that depend somewhat on the chosen resolution.

Given the plate scale (~0.125 arcsecs/pixel) which was optimized for imaging, the OSIRIS spectroscopy mode is somewhat oversampled, which is not a bad feature per se but, counting on "only" 4102 pixels along the dispersion, the one-octave wavelength coverage is limited to resolutions R~1000. Nevertheless, for the very competitive R=2500 spectral resolution OSIRIS provides enough highly-efficient grisms to cover the whole optical range in four wavelength intervals. The highest R=5000 resolution, at the moment is available only in the red ($0.8 \leq \lambda[\mu m] \leq 0.93$), but specific science programs could purchase other R=5000 grisms as required. In spectroscopy OSIRIS also delivers a competitive field of view, considerably larger than similar instruments of its class, like GMOS (Gemini) and LRES (Keck), but naturally delivering a smaller spectroscopic field than much larger (and significantly more expensive) wide-field MOS spectrographs such as DEIMOS (Keck) & VIMOS (VLT).

The instrument throughput is remarkably competitive. Its optical transmission (excluding dispersive elements and detector) is significantly better at all wavelengths than similar instruments like FORS (VLT), GMOS (GEMINI), and LRIS (Keck). Overall, OSIRIS is a competitive instrument in its class, with the extra advantage of tunable imaging, making it quite a competitive and adaptable workhorse optical instrument for broad and narrow band imaging and low-to-intermediate (R<~5000) spectroscopy.

b. CanariCam

CanariCam is the second “first light” instrument for GTC, and will serve as the facility mid-infrared instrument. CanariCam has four science modes and two engineering modes, which use the same 320 × 240-pixel, arsenic-doped silicon, blocked-impurity-band detector from Raytheon. CanariCam represents an evolution of the successful instrument design of T-ReCS, the Gemini South facility mid-IR imager/spectrometer commissioned in summer 2003, which was also designed and built at the University of Florida. Each mode can be remotely selected quickly during an observing sequence. The pixel scale is 0.08 arcsec, resulting in Nyquist sampling of the diffraction-limited point-spread-function at 8 microns, the shortest wavelength for which CanariCam is optimized. The total available field of view for imaging is 26 arcsec × 19 arcsec. The primary science mode will be diffraction-limited imaging using one of several available spectral filters in the 10μm (around 7.5-13.5 μm) and 20 μm (around 16-26 μm) atmospheric windows. Any one of four plane gratings can be inserted for low and moderate-resolution (R = 60 - 1300) slit spectroscopy in the 10 and 20-μm regions. In the 10 μm window, insertion of appropriate field and Lyot stops converts the camera into a coronagraph, while insertion of an internal rotating half-wave plate, a field mask, and a Wollaston prism converts the camera into a dual-beam polarimeter.

c. EMIR

EMIR is the facility wide-field near-infrared (NIR) imager and multi-object spectrograph for the GTC. EMIR provides a 6x6-arcmin imaging FOV, with broadband filters covering the 0.9-2.5-micron wavelength range. It also uses a cryogenic configurable slit unit for multi-object spectroscopy of up to ~50 targets simultaneously over a 6x4-acrmin field of view. Spectroscopic resolution provided by pseudo-grism dispersers range from R ~5,000 in the K-band to R ~4,000 in the J-band. EMIR is a general-purpose instrument, with a wide range of capabilities, and a design optimized for multi-object spectroscopy of high-redshift galaxies in the K-band.

d. CIRCE

The Canarias InfraRed Camera Experiment (CIRCE) is a near-first-light near-infrared (1-2.5 micron) instrument. While the EMIR instrument is scheduled to come on-line for GTC sometime after first light, CIRCE will be the only NIR instrument available for GTC for its first period of operation, and will thus fill a crucial gap in “first-light" instrumentation between the other facility instruments: OSIRIS and CanariCam. In addition, the optics and detector array of CIRCE will provide a pixel scale (0.10 arcsec/pixel) fine enough to properly sample the excellent images provided by GTC, while at the same time providing a near-IR field-of-view (3.4x3.4-arcmin) comparable to any currently available on the world's large telescopes (areal FOV ~25 times larger than NIRC on Keck, and ~3 times larger than NIRI on Gemini). In addition, after the delivery of EMIR, CIRCE will continue in scientific use on the GTC Bent Cassegrain “visitor" ports, where its high image quality and resolution, polarimetric capability, high time-resolution readout, and lower spectral resolution (useful for very faint targets) will complement the capabilities of EMIR and continue to augment the scientific capabilities of one of the world's largest optical/infrared telescopes.

e. FRIDA/GTC-AO

FRIDA and the GTC Adaptive Optics systems (GTC-AO) will provide near-diffraction-limited imaging and integral field spectroscopy over the 0.9-2.5-micron bandpass on the GTC. GTCAO will initially provide natural-guide-star correction over the isoplanatic patch with Strehl ratios as high as ~65% in the K-band. A planned upgrade of GTCAO will provide a laser guide star with similar Strehl ratio and dramatically improved sky coverage. FRIDA has two main science pixel scales of 10-mas/pixel and 20-mas/pixel, allowing adequate/good sampling of the diffraction-limited PSF over the JHK bandpass with fields of view exceeding the expected isoplanatic patch size. In addition, FRIDA will have integral field spectroscopic capabilities using an image slicer with 3 selectable spaxel scales and fields of view matched to various science cases and resolutions from R ~1,000 up to R~30,000.

2. Other observatories now

a. 8-m to 10-m observatories

Table 1 *– The following table summarizes the main present-day large optical and infrared observatories.*

Facility	Aperture (m)	Observatory	Partners
LBT	11.3 2x8.4	Mt. Graham, Arizona USA	Arizona, Italy, Germany, Ohio State U., Research Corporation. (OSU, NDU, UMin, UVir)
GTC	10.4	ORM, La Palma Spain	Spain, México & U. Florida
Keck I & II	2 x 10.0	Mauna Kea, Hawaii USA	Caltech, U. California, NASA
SALT	9.8	Northern Cape, S. Africa	S. Africa, HET, Poland, India, UKSC, Göttingen & several USA universities.
HET	9.2	Mt. Fowlkes, Texas USA	U Texas, Penn State, Stanford, Munich (LMU), Göttingen (GAU)
Subaru	8.3	Mauna Kea, Hawaii USA	National Astronomical Observatory of Japan
VLT	4 x 8.2	Cerro Paranal, Chile	European Southern Observatory (ESO)
GEMINI-N	8.1	Mauna Kea, Hawaii USA	USA, UK, Canada, Australia, Argentina, Brazil & Chile
GEMINI-S	8.1	Cerro Pachón, Chile	
Magellan	2 x 6.5	Las Campanas, Chile	Carnegie, U. Arizona, Harvard/CfA, U. Michigan, MIT
MMT	6.5	Mt. Hopkins, Arizona USA	Harvard/CfA, U. Arizona

It is clear that the most powerful astronomical countries and institutions have either developed or have access to large aperture observatories. Most of these consortia are highly capable of operating their facilities and developing competitive and up to date instrumentation, so it will not be an easy task for GTC to excel among them. GTC can only be competitive with a proper combination of its slightly-larger aperture with a set of carefully chosen instruments and telescope capabilities matched to the properties, strengths and growing plans of its particular scientific community. Among all these observatories the ESO/VLT is particularly important for defining the context for the second generation of GTC instruments, and several specific references to its individual instruments will be made later in the report.

b. *Wide-field surveys (i.e. Sloan, Vista, LSST, PAN-STARRS)*

One of the possible drivers for future GTC instrumentation is to take advantage of current and planned large surveys. These could lead to the design of instruments particularly well-suited for the follow-up of such surveys. Due to its relatively limited field-of-view (FOV) GTC is not well-optimized for large-scale surveys – the "A" advantage GTC enjoys in area can be overcome by the "Ω" advantage of other smaller telescope. Thus, surveys with GTC should concentrate on depth and probably specialize in narrow-band filters and spectroscopy.

For our purposes, the primary surveys of interest would be ending around 2011-12 (end of first-generation instrument construction and beginning of the second generation) and around 2017 (end of second-generation instrument construction). Below we give some numbers for the largest ground-based surveys, either finished, ongoing or planned. For a full discussion, space-based surveys like GAIA, which should extend up to 2020, should be added to the list.

Table 2 – Ground-based surveys. This list, including the largest planned (or nearly finished) surveys, is provided to orient the reader. Most data have been extracted from the official web pages or from conversations with scientists closely related to the projects.

	LSST	Pan-Starrs	UKIDSS	VHS	VIKING	IPHAS	DES	SDSS I+II
Wavelength	Visible	Visible	NIR	NIR	Red-NIR	red	red	Visible
Area (deg^2)	20000	30000	7500	20000	1500	1800	5000	8000
Hemisphere	South	North	North	South	South	North	South	North
Begin	2014	2010	2005	2010	2010	2003	2010	2002
End	2019		2012	2015	2015	2008	2015	2008

The surveys closest to the 2017 date are the Pan-Starrs and LSST surveys (Pan-Starrs has no completion date, but it can be estimated to reach a depth comparable to LSST). LSST is in the South and will share with GTC a band of ±20 degrees (or slightly more) around the celestial equator, while Pan-Starrs will nearly overlap in sky coverage with GTC. Both share sufficient sky with GTC to be considered interesting. The Dark Energy

Survey (DES) is still trying to get the required funds (although there are good prospects for doing so). Planned for a 5-year duration, the expectation is that it will be finished slightly before 2017 (present schedule is 2010-2015). Again, making use of the Victor M. Blanco 4m telescope (CTIO) the sky overlap with GTC will be limited as LSST. The same situation arises with the planned VISTA and (more uncertain) VST surveys – expected to end about 2015 and limited sky overlap with GTC (although a bit more than LSST and DES). Another interesting survey is UKIDSS, which will be finished by 2012 and from which there have already been three data releases.

Surveys such as SDSS I and II or IPHAS can also be considered, but they should not drive future GTC instrumentation as strongly, as their exploitation is currently underway. OSIRIS and EMIR are adequate for follow-up spectroscopy of objects detected in these surveys. Surveys like Alhambra or OTELO have a special interest because they are rooted in the GTC community, but they have a much smaller field than others considered here. They can, however, be very efficient users of GTC instrumentation and should be taken into account when deciding about observing modes of planned instruments, but again should not drive future GTC instrumentation (with the possible exception that the involved teams want to propose instrument projects dedicated to that purpose).

Therefore the ground-based surveys that are most relevant for the context of GTC future instrumentation are LSST, Pan-Starrs, UKIDSS and DES. UKIDSS will be finished relatively early, so that its interest could be limited to some specific aspects (f.e., a subsample of objects with given characteristics). DES and LSST surveys may also be advantageous, but the large 8m telescope in the South will be in better position to take advantage of them. Finally, surveys rooted in the GTC community may use general purpose instrumentation and even influence it. However, dedicated instrumentation, although interesting, should be considered with caution in view of the limited resources available (foci, observing time, budget, manpower). The effort in such cases should rely more in the interested groups.

c. *Space (HST, Spitzer, etc.)*

The successful synergy between Hubble Space Telescope (HST) and Keck and VLT is expected to be extended in the future to GTC too. This will be especially true if the ambitious SM4 (Servicing Mission Four) plan to refurnish HST is completed. Under this assumption, HST's operational life will be extended by at least five years, and its imaging capabilities will be boosted by the installation of WFC3 (and the recovery of the ACS). As a generic rule of thumb, deep spectroscopic observations in the optical and near-infrared wavelengths with ground-based 8- to 10-m-class telescopes and high angular resolution HST imaging nicely complement each other for many studies (e.g. high-z galaxy population studies). On the other hand, the installation of the Cosmic Origins Spectrograph (COS) on HST will provide UV observations with unprecedented sensitivity in the 1150-3200Å spectral range – a region inaccessible from the ground. The opening of this new window will certainly require complementary spectroscopic observations in optical and near infrared, which are most efficiently obtained from the ground. In summary, complementarity with HST calls for efficient optical and near-infrared spectrographs for GTC.

Despite its small aperture, Spitzer provides full access to the spectral range 3 - 180 microns with unprecedented sensitivities. Ground based 10-m-class telescopes cannot compete in terms of sensitivity with Spitzer in the mid-IR (even in the N band with diffraction limited observations) as a consequence of the high level of background produced by the atmosphere at these wavelengths. This disadvantage is even more dramatic in the Q band, where the atmosphere shows high variability. GTC should provide complementary capabilities, mainly in the optical and near infrared (up to 2.5 microns) spectral range with both imaging and spectroscopic observations. However, in terms of angular resolution, GTC mid-infrared observations have the potential to greatly improve the relatively poor angular resolution provided by Spitzer at these wavelengths, even for seeing-limited observations. Obviously optical/near-infrared GTC instruments will provide angular resolutions much better than those reachable with Spitzer, specially if they are assisted by AO systems.

There are many other current astronomy space missions such as XMM-Newton, INTEGRAL, SWIFT, and CoRoT. Although complementarities among all these facilities are expected for some studies, they are well served by planned GTC instrumentation and the proposed medium-resolution optical spectrograph.

3. Other observatories in the future

The future context for GTC instrumentation will of course include all of the facilities listed in I.B.2 above. In addition, we note four broad categories of new future capabilities which will be coming on-line during the timescale considered for this report. These include Extremely Large Telescopes (ELTs), the James Webb Space Telescope (JWST), the Atacama Large Millimeter Array (ALMA), and a broad category of "other future space missions". We briefly describe each of these below.

a. ELTs

One of the most obvious areas where future observatories will impact the GTC will be the advent of the "Extremely Large Telescopes". Much as Keck, the 8-meter telescopes, and now GTC are revolutionizing the astronomical world previously dominated by 4-meter and 5-meter telescope, the ELTs – with apertures from 20-m to 42-m in diameter – will re-define the astronomical world of the future. The leading projects envisioned now include the Giant Magellan Telescope (GMT – 20-m diameter), the Thirty Meter Telescope (TMT – 30-m diameter), and the European ELT (E-ELT – 42-m diameter). These observatories will include a broad range of scientific capabilities, running the gamut from optical seeing-limited observations to diffraction-limited observations in the near- and mid-infrared wavebands. While the first light capabilities – coming on-line in the next 5-10 years – may be initially somewhat limited by instrument choices, we can assume that in the long-term (i.e. 2020 and beyond) these telescope will have a similar suite of instruments to match those of the current generation of large telescopes.

b. JWST

JWST will serve the international community at large (similarly to HST), and is also expected to make fundamental breakthroughs in many fields of Astronomy. According to the current schedule JWST will be launched during mid-2013, and will be operational for 5/10 years (requirement/goal). Therefore, the timeframe for JWST fits well with that considered for a second generation of GTC instruments.

Unique capabilities of JWST over ground optical/infrared telescopes are:

- Sensitivity: JWST imaging is unique in terms of sensitivity beyond 1.7 microns even for a 30m telescope in imaging and low/moderate-resolution spectroscopy (e.g. Science Assessment Team, 2005).
- Continuous spectral coverage from 0.6 to 28μm,
- Good and stable PSF over a wide FoV, with diffraction limited observations for $\lambda > 1.7$ μm.

It is expected that GTC, like other major ground-based telescopes, will complement JWST observations. The following are complementary areas for GTC:

- High spectral resolution (>3000) spectroscopy. JWST lacks this capability.
- UV-Visible accessibility below 0.6 microns. This spectral range is not covered by JWST. This will be particularly important after HST is decommissioned.
- GTC+AO has higher spatial resolution than JWST. In the mid infrared, under good seeing conditions GTC will approach the diffraction limit, which is also higher than JWST.
- Accessibility to a larger FoV. JWST imaging and spectroscopic (MOS) instruments have few arcminute squared FoV (i.e. ≤ 3’ x 3’), while GTC could take advantage of substantially larger values.
- Multi-IFU observations. This capability is not provided by JWST.
- Flexible time allocation. Important for targets of opportunity.
- Upgradeable and versatile. GTC (ground) should take full advantage with respect to the less flexible space facilities to improve and adapt its instrumentation.

The different nature of these two telescopes, and the fact that they serve to quite different communities does not recommend to guide the GTC instrumentation by the list above. However, such a list may provide additional information when different GTC instrument options are considered.

c. ALMA and LMT

ALMA is the ultimate observatory for the millimeter and sub-millimeter spectral region. Its construction is properly advancing and it will be in operation well in time to complete the set of next generation observatories (together with JWST, the optical/IR ELTs, the EVLA and the rest of main space missions). There is no other facility of its kind planned for the foreseen future, and it is therefore a well-coordinated international effort among all main astronomical world powers (ESO, North America and Japan, among others). Naturally, GTC is in fact considered a part of the synergistic and follow-up facilities for ALMA.

The main ALMA science driver is the unique observation of the cold universe, which includes the detection of a large number of newly-discovered galaxies particularly at high redshifts ($z>1.5$). GTC will not be the optimal telescope for ALMA follow-up surveys, but certainly a great tool to study selected ALMA samples and their environment, mostly through NIR spectroscopy and narrow- and broad-band imaging in the optical, NIR and mid-IR. For galactic objects, GTC could help with AO observations of the closest cold objects detected, before the ELTs become fully operational.

Since the main GTC partnership is involved in the ALMA project, the GTC future instrumentation already has ALMA as an integral part of its planning, through the knowledge and influence within the relevant governing boards (ALMA, ESO, NSF, etc), but most importantly through the work and collaborations of the GTC scientific community in ALMA-related projects. Therefore, the GTC instrumentation and operations are already and will continue to be naturally responding well to synergies and exploitation of the ALMA science plans and products.

Another important upcoming facility in this bandpass is the Large Millimeter Telescope in Mexico, for which INAOE plays a leading role. LMT will provide an important complement to ALMA capabilities, both internal and external to the GTC partnership. Also, LMT shares a similar latitude, and thus sky coverage, with GTC. Potential synergies between this facility and GTC future instrumentation should be given appropriate weight in evaluating priorities.

d. Other space missions

In the coming years other space missions with participation from GTC partner countries/institutions, such as HERSCHEL and GAIA, will probably require GTC follow-up observations.

GAIA (scheduled to be launched in Dec. 2011) will provide unprecedented astrometric measurements for about one billion stars in our Galaxy and throughout the Local Group. GAIA also has photometric and high resolution spectroscopic capabilities. However, its high-resolution spectroscopy is limited in sensitivity and spectral range (847-874nm), being in practice only feasible for a small fraction of the sample for which high precision astrometry and photometry will be obtained. Therefore, follow up complementary observations with GTC call for a medium/high-resolution (R~20000) optical spectrograph with multiplexing capability. That will make possible to obtain radial velocities and perform abundance analyses for most of the stars contained in the sample observed by GAIA. Also an optical IFU capability in the GTC will permit spectroscopy of very dense regions observed with GAIA.

HERSCHEL (planned to be launched in 2008) is optimized from the far-infrared to sub-millimeter wavebands and, though complementary observations with GTC are expected for some studies, we do not foresee a clear specific call for a particular type of instrumentation. However, high angular and spectral resolution near-infrared spectroscopy with GTC may probably be needed for objects with molecules associated to circumstellar disks detected by HERSCHEL, which will be well served by current instrumentation.

WSO (World Space Observatory) is a space based UV-mission led by Russia, consisting of a 1.7-m telescope and two UV spectrographs (R= 55000 and R=1500-2500), as well as UV and optical imaging capabilities. Spain has strong participation in WSO, and therefore its community will have privileged access to the data and observing time. Therefore, WSO may constitute also an important source of targets for GTC, in particular taking into account that it is the only UV mission planned after HST.

II. Near-Future Instrumentation

In this section, we present analyses of the GTC instrumentation capabilities and priorities for the Near-Future term – meaning from the present moment to instruments which may begin coming on-line in 2013 and beyond. In Section II.A we present a description of our basic motivation and approach used for this analysis. In Section II.B we present specific recommendations derived from this approach, including specific instruments we recommend for study, and specific issues for which the GTC Project requested analyses on the UES and SIDE instruments. In Section II.C we present recommendation for GTC operations related to instrumentation capabilities. In Section II.D we present the timeline and rough budget estimate for these recommendations. Finally, in Section II.E we present a summary of the key recommendations for the Near-Future term.

A. Motivation/Approach

1. Workhorse instruments

GTC primarily serves a specific user community in Spain, Mexico, and at the University of Florida. This community is broad in its scientific interests and hence its instrumentation needs are also diverse. The GTC will fulfill an essential role for a large fraction of this community since it will provide prime large telescope access to the Northern skies. Because of these particular circumstances and to serve the community in the best possible way, GTC must achieve a good balance between hosting general-use workhorse instruments and instruments optimized for a specific capability driven by a very specific science goal. Instruments with a broad, and therefore less-specific, science case may appear less convincing in the absence of a “killer” application. However, such general-purpose instruments, if well-designed, are likely to attract a broad community of users and will find use in novel science programs unforeseen at the time of their conception. So, high quality work-horse instruments have long prospective competitive lives. Many future science programs – for instance those linked to space missions requiring ground-based complementary observations, or for target-of-opportunity observations – will need basic (but high-quality) optical and near-IR spectroscopic and imaging capability that GTC should provide.

Such workhorse capability should focus on:

- High-throughput optical and near-IR imaging, exploiting natural seeing and delivering the widest reasonably available field.
- High-throughput optical and near-IR medium-resolution spectroscopy, exploiting natural seeing and delivering the widest reasonably-available field and multiplex gain.

- Although it is still early for GTC to conceive routine AO operations, a near-IR high-spatial-resolution imager/spectrograph should be also considered a modern-day work-horse instrument.

Good examples of such high-quality general-purpose instrument are the XShooter optical and near-IR spectrograph that will be the first of the second-generation instruments on the VLT or the AAOmega VPH articulated spectrograph on the Anglo-Australian Telescope.

It is important to realize that highly-stable workhorse instruments become much more powerful through time, as the broad user community builds up a highly reliable set of calibrations, reduction packages, data bases and overall wide application experience to exploit the instrument capabilities to its ultimate limit. Ease-of-use and the ability to quickly obtain reduced and publishable data is very important for effective work-horse instruments.

For the reasons mentioned above GTC should not hold back on deploying general-purpose instruments even if there is no obvious “killer” application, or when similar capability is available at other telescopes, as long as such instruments are competitive.

2. Covering Parameter Space

Given the unique role that GTC plays within its user community, it will be important that GTC’s instrumentation suite covers the most essential instrument capabilities. The planned set of instruments actually already provides for a very good coverage of wavelengths and spectral resolutions. The diagram below crudely indicates for each instrument which area is covered in the resolution-versus-wavelength parameter space. Colored areas refer to approved instruments, while the grey outlines are for two proposed instruments. (Note that SIDE is a proposed multi-object fibre spectrograph, and UES a refurbished fibre-fed echelle spectrograph)

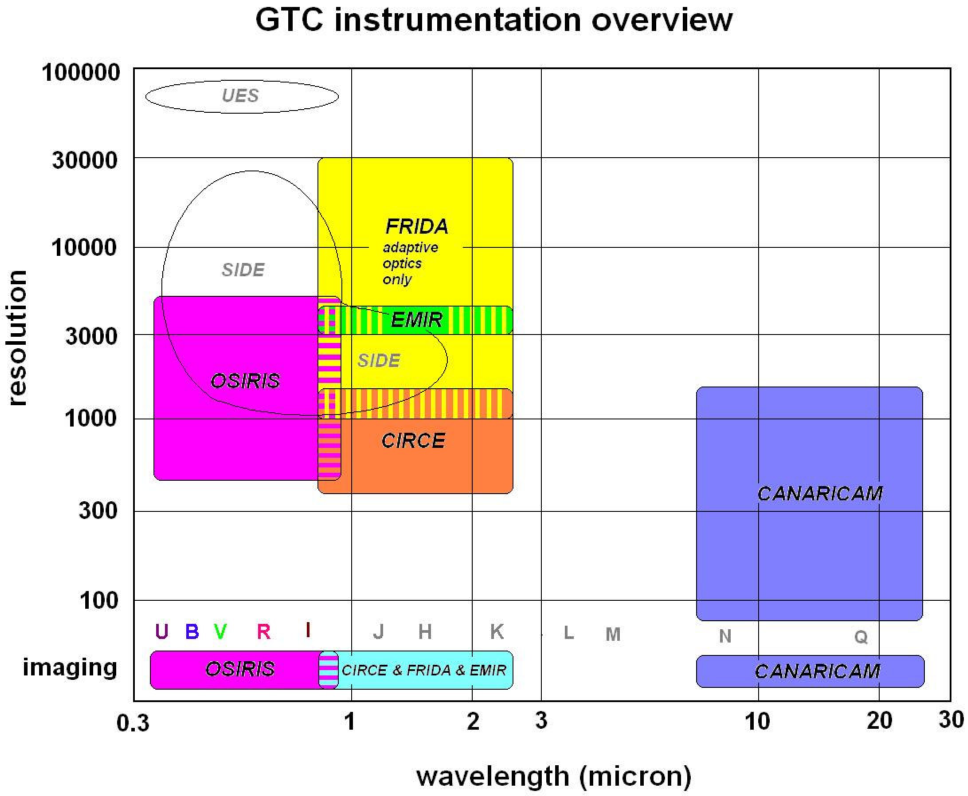

Figure 1 *– Parameter space for GTC instrumentation*

The diagram obviously simplifies reality and does not show full technical detail and capability of each instrument, such as multiplexing capability, field-of-view, polarimetric capability, or image quality and delivered Strehl ratio. However, it may serve as an overview and guide as to where specific overlap or gaps in basic capability lie.

From the above diagram we conclude that there are four areas in the approved instrumentation suite where capability is lacking: (i) medium-resolution optical spectroscopy, (ii) high-resolution optical spectroscopy, (iii) medium/high-resolution near-IR spectroscopy, (iv) medium/high-resolution mid-IR spectroscopy (though poor sensitivity may be a serious limiting factor here). We note that L and M-band imaging and spectroscopy can be covered by CanariCam, although these bands are not part of its main design drivers. Medium-resolution optical spectroscopy has already been identified by GTC as a key development area (see further discussion in section II.B below). Furthermore, for high-resolution optical spectroscopy, an attractive fast-track solution is offered by the deployment of an existing (but refurbished) instrument – UES – provided it will be competitive. We consider that another high priority for GTC to consider will be a medium-/high-resolution seeing-limited near-IR spectroscopic instrument. Close competitors of such instrument at other large telescopes are NIRSPEC on KECK-II and CRIRES on the VLT.

For future new instruments in general multiplexing capability is highly desirable and partly catered for already through planned instrumentation. In each case such capability needs to be justified through a detailed scientific, technical and budgetary analysis.

B. Specific Instruments Recommended for Study

In this section, we further describe the two primary instruments we have identified for study as near-future instruments for the GTC. As noted above, carrying out detailed studies of science drivers, technical capabilities, and science/technical/cost/risk trade studies for such instruments are all well beyond the scope of this report. Furthermore, such studies are best carried out by larger instrument teams drawn from the GTC community as a whole, so that the interests of the community are properly represented. Our purpose here is to provide the GTC Project Office and the GTC community with enough definition of the likely instrument parameters to allow the initiation of such in-depth studies. In Section II.B.1 we describe the medium-resolution optical spectrograph. In Section II.B.2, we describe the medium/high-resolution near-infrared spectrograph. In Section II.B.3, we address specific issues for the SIDE and UES instruments proposed for the GTC, as requested by the GTC Project Office.

1. Optical spectrograph at R>10,000

A mid-resolution optical spectrograph (R=10000-20000) has already been recommended by the SAC as the next instrument that should be developed by the GTC. We fully agree with this recommendation. This should be a workhorse, multi-purpose instrument aimed at giving support to a large number of projects. As stated above, it should be an instrument with significant multiplexing capability, not only to take advantage of large surveys, but also because in current research many results have been reached only after analyzing a large number of objects. Possible references (and competitors) would be FLAMES-GIRAFFE and MUSE at the VLT or WFMOS at Subaru. Note that at present there is no such an instrument operating in the northern hemisphere, and only GMOS, with limited resolution, would be a competitor in the blue (DEIMOS at Keck II is also a competitor in the red). The so-called “high-resolution” spectrograph included in the current SIDE proposal may be an adequate solution (although of course other approaches are also possible). The low resolution part of SIDE does not contribute to the merit function of GTC in terms of resolution, as this is already covered by OSIRIS and EMIR (although the proposed multiplexing capability of SIDE may be significantly larger – see Section II.B.3.a for further discussion).

2. NIR seeing-limited spectrograph at R>10,000

The region of R=10000-20000 in the near-infrared (NIR) seems to be already covered in Figure 1 by FRIDA, but this is an adaptive-optics instrument and its field of view is consequently limited (on the order of one to a few square-arcseconds). In the last decades, the effort in the NIR, both observational and theoretical, has been enormous and the same arguments that can be used for an optical mid-resolution spectrograph can be applied to the NIR range. The same kind of studies (kinematics, abundances, stellar and ISM properties, galactic structure, etc.) can be performed in the NIR, with the obvious advantages of the much lower extinction and the access to cool, red objects. A seeing-limited, NIR instrument with R~20000, multiplexing capability of a few to few x10 over a large patrol field of view, and broad wavelength coverage would thus be a very important workhorse instrument with large applicability. We recommend such an instrument, which has not been planned or proposed for GTC, nor is planned or available at any other 8- to 10-m telescope.

An instrument at much larger spectral resolution (R=150,000, NAHUAL) has been proposed. Such an instrument would be preferentially dedicated to high-precision radial velocity studies and could also be used for the identification of new spectral features (separating contributions blended at lower resolutions or revealing faint lines). Here again we have the same situation as in the optical with UES, though perhaps with a more focused, less-extended interest in the GTC community. Although here the competitiveness and the interest of the particular scientific case is clear, the higher cost and the more limited use as a general instrument require specific study to determine whether this instrument may also be of interest as a priority for GTC.

3. Other specific considerations

In this subsection, we consider two specific issues as requested by the GTC Project Office. Specifically, the GTC project office has asked us to consider whether or not the proposed SIDE and UES instruments, if they are NOT available on the GTC, would leave significant gaps which the GTC would need to fill at high priority. We first consider the proposed SIDE instrument and then the proposed UES upgrade.

a. SIDE

The mid-resolution optical spectroscopy (R=10000-20000) is another region clearly not covered presently by GTC (i.e., by one of the instruments in construction or already approved) but is a field of large interest for the GTC community, as it has already been recognized by the SAC, who recommended an instrument with these characteristics – see also section II.B.1. The higher-resolution portion of SIDE as currently proposed would seem to adequately fulfill this need for the GTC community. However, it is the understanding of this Working Group that the primary cost/resource drivers for the current SIDE proposal derive from the low-resolution optical/near-infrared portions of the SIDE spectrograph. These portions of the SIDE proposal do not have any positive impact on the merit criteria we have established here – on the contrary, they contribute to a substantial increase in risk and cost. Other groups/committees are currently being commissioned to review the SIDE proposal as a whole, and will presumably pay close attention to the issues of whether the scientific gains which may actually be realized by the lower-resolution portion of SIDE are sufficient to motivate these dominant cost/resource/risk drivers, especially given the existing multi-object spectroscopic capabilities provided by OSIRIS and EMIR on the GTC.

b. High-res optical (i.e. UES)

High resolution spectroscopy requires a large number of photons. Except for specific projects, only the largest telescopes at each moment can be really competitive. Therefore, high-resolution spectroscopy is one of the fields in which GTC will be very competitive due to its large collecting area. As it can be seen in Figure 1, this is a region of the instrumental parameter space not currently covered by GTC (neither in the optical nor in the NIR). In addition, in the northern hemisphere only HIRES is a competitor on a similarly-large telescope; in the South, UVES and Espresso will be serious competitors.

An advantage of optical high-resolution spectroscopy is that the data needed for full analysis (i.e. atomic line databases) are fairly complete and the physical processes involved are well understood (without meaning that we know everything). This allows us a good interpretation of the observations. However, high-resolution spectroscopy is a very specialized field. It is therefore important to explore whether there is sufficient interest in the community to which it is addressed. While this has to be done by consulting the GTC scientific community, we may identify a few fields in which optical high-resolution (R>30,000) spectroscopy can be of interest (without pretending to be complete).

- Abundances in the ISM at large and intermediate z (Lα forest, Damped Lα systems, quasars, starbursts and star forming galaxies) and in the Local Universe
- Stellar structure and atmospheres: pulsations, line asymmetries, abundances in slowly rotating stars or low density environments (chromospheres, super- and hypergiants), detection of weak lines
- High precision radial velocity studies in all kind of objects, and high-order moments of velocity distributions (e.g. anisotropy, tri-axiality, etc.) in unresolved stellar systems and galaxy nuclei.

These areas cannot be properly covered at lower resolution, even using high S/N ratios. There are groups in the GTC community working in topics related to all these areas. Therefore we recommend that the GTC Project Office commission a small study or working group to seriously explore interest in the GTC community and study the costs/benefits at issue. The UES proposal in particular should be seriously considered, because it may offer a relatively high benefit at low cost, but a study to confirm the competitiveness and interest of the specific proposal should be performed (including sensitivity, wavelength coverage, target multiplex, velocity precision/stability and science drivers).

C. Recommendations for GTC Operations Models

1. Queue-scheduled observing

a. Importance

An important advantage of the GTC operational model will be the use of queue scheduled observing. If implemented well, with due care to scheduling in accordance to scientific priority and environmental parameters (e.g. sky brightness, seeing, transparency) and with attention to quality control, queue scheduled observing could be an important factor in the overall scientific efficacy and success of the telescope. Queue scheduled observing is particularly relevant for observations that require special environmental circumstances, such as exceptionally good atmospheric turbulence conditions for adaptive optics observations or low water vapor conditions for mid-IR observations. But in addition to observations that have such special requirements, in general terms queue scheduled observing can drastically increase the success rate of the top tier of observing proposals because scheduling flexibility makes them less susceptible to statistical fluctuations of the weather.

Broadly speaking, in queue scheduled observing mode the observations that are carried out during some night are not simply conducted according to a pre-defined schedule, but rather depend on the scientific ranking and the match of the observing requirements to the actual environmental conditions and the instruments available at that time. Based on established statistical knowledge of the observing conditions one can predict the chance of success of a certain program and with high fidelity guarantee that a specific program will be successfully completed within a certain period of time. Hence the success of an observation is much less a matter of good fortune, such as is the case in classical observing mode. In this way top-ranked proposals will experience a very high (~100%) success rate providing that the queue is managed well.

An important added benefit of queue scheduled observing is that the prevailing environmental conditions can be exploited in a fashion that is more optimal than in classical visitor-observing mode. For instance, good seeing conditions can be used for the scientifically most important programs that indeed require good seeing, rather than that such favorable conditions are used for programs that don’t require it. Also, flexible scheduling during the night allows making optimal use of dark, Moon-less skies, even on nights when the Moon is in the sky only part of the night, thus increasing the amount of valuable dark time.

b. *Requirements*

Queue scheduled observing requires that observatory personnel carry out the observations for reasons of complexity of possible changes in instruments or observing modes, for the need to conduct quality control so that a good data product will be delivered, and to ensure that the queue is accurately managed. Although the cost to the observatory in terms of effort required will be relatively large, the potential payoff in more and better science being delivered will also be large.

Choosing queue scheduled observing mode as such does not directly influence GTC's instrumentation development plans, but instruments should be suitable for queue scheduled observing and facilitate fast deployment and returning to stand-by mode. GTC operation should be prepared to switch between instruments during the night. Ideally, observations should be carried out in an automated fashion directly from the phase-2 observing proposal. This requires that the telescope and instrument can be controlled from a central sequencer. With its various focal stations available on GTC, this telescope is in principle ideally suited for queue scheduled observing and hence for reaping its benefits.

2. Visitor or "PI" Instruments

a. *Importance*

GTC may well wish to position itself as a platform for the deployment of visiting instruments. With visiting instruments we refer broadly speaking to instruments that are not developed, funded, or owned by GTC and will typically not be integrated fully into the GTC infrastructure as common-user tools for the wider community. The key reasons for hosting visiting instruments are: (i) they allow fast-track execution of very specific scientific projects that require an optimized instrument matching that narrow science goal. The science is usually urgent and novel, and since the instrument developers have a very specific goal in mind the scientific return comes usually fast and is significant. (ii) major scientific developments are often based around novel measuring techniques or observing methods. If proven successful, such techniques could later be incorporated into common-user instruments.

For both abovementioned aspects the GTC will receive positive press and "brownie points" in the user community. But more importantly, it will attract users, ideas, and new resources for instrumentation development that would otherwise not be available.

b. *Requirements*

But there is a price to pay: hosting visiting instruments tends to be time consuming for the observatory. There are many interface issues to deal with, usually requiring adaptations to infrastructure hardware and software. It requires negotiation and preparation, freight and administration, and much on-the-spot intervention and creativity. If not properly managed, visiting instruments can significantly distract observatory personnel from the normal day-to-day routine.

If GTC wants to welcome visiting instruments it needs to agree rules-of-engagement covering issues such as data ownership, interface standards, instrument use by others, available foci, etcetera. Having such guidelines prepared will reduce unpleasant surprises.

D. Timeline/budget

In order to have the above-recommended instruments operational at the telescope by 2013, their definition and development should begin immediately. An optical mid-R spectrograph was approved and sought by GTC since late 2002, and since the higher-resolution portion of the SIDE instrument is already providing a conceptual design for such a capability, such instrument should then be constructed and commissioned by 2013 in principle. On the other hand, we are not aware of any proposal for the NIR medium-/high-resolution spectrograph, so GTC should launch this initiative by the end of 2008.

Although standard Instrument Definition Teams should be sufficient to define the instrument concepts, it is important before kickoff, to develop a set of general high-level requirements for both optical and near-infrared workhorse spectrographs with the input of the GTC scientific community. Since none of these instruments requires particularly novel developments, nor needs unproven technologies, they both can go through all design, building and commissioning phases by 2013, provided that the IDT and GTC community do not demand severe extra capabilities and over-complexity that may compromise their development or success.

For the same reasons – fast and secured delivery with no-need for extra complexity – the budget required for these missing capabilities should not be excessive. A very rough estimate of the price for each instrument (including personnel) would be approximately eight to ten million Euros.

We have not included the UES proposal here, in that we expect its cost to be relatively small if the GTC community decides to implement it. We also note that the estimated total cost of SIDE significantly exceeds the above estimate by many millions of Euros. However, we believe this cost difference is driven by the lower-resolution portions of SIDE, which do not address the highest priority needs we have identified here.

E. Summary of Near-Future (2013+) Recommendations

We present here a brief summary of the key points and recommendations of the analyses for the Near-Future term (i.e. capabilities that will be coming on-sky beginning around 2013):

- GTC should develop a medium-resolution (R ~ 10,000 - 30,000) multi-object optical spectrograph, as described above, for on-sky commissioning in 2013. The estimated total cost of this project is 8-10 million Euros (including manpower). We note that such an instrument has already been formally endorsed by the GTC SAC and various other governing bodies in the GTC community.
- GTC should develop a medium-resolution (R ~ 10,000 - 30,000) multi-object near-infrared spectrograph, as described above, for on-sky commissioning in 2013. The estimated total cost of this project is 8-10 million Euros (including manpower). This timeline would require the initiation of a feasibility study for such an instrument in 2008.
- Queue-scheduled observations will be critical to optimizing the scientific return of the GTC, and should be fully supported.
- Visitor or "PI" instruments provide an important contribution to the potential scientific flexibility and productivity of the GTC, and the GTC should develop clear guidelines for working with such instruments.
- The "high-resolution" portion of the proposed SIDE instrument would seem to fulfill the requirements for the medium-resolution optical spectrograph (as we define the terms here). The low-resolution and infrared portions of the SIDE instrument would not seem to contribute directly to the merit criteria we have established here.
- High-resolution optical spectroscopy is an important scientific niche which particularly benefits from the large collecting area of the GTC. GTC should commission a study as soon as possible to assess the suitability of the UES instrument for meeting the scientific needs of the GTC community in this area, as well as possible alternative plans for this capability.
- A well-defined funding (and monitoring) scheme, well-adapted to the schedule and milestones of these projects, is highly recommended to optimize resources and achieve the desired results on time. The specificity of these generally multi-national, multi-institutional projects may require optimization of the general structure under which they are developed.

III. Mid-Future Instrumentation

In this section, we present analyses of the GTC instrumentation capabilities and priorities for the Mid-Future term – meaning instruments which may begin coming on-line in 2018 and beyond. In Section III.A we present a description of high-priority adaptive optics options/capabilities for the GTC in the Mid-Future term. In Section III.B we present a description of other instrumentation priorities which may possibly arise in the Mid-Future term. In Section III.C we present the timeline and rough budget estimate for these recommendations. Finally, in Section III.D we present a summary of the key recommendations for the Mid-Future term. We note that this section has an obvious emphasis on adaptive optics instrumentation. As we show below, this emphasis arises naturally due to both the intrinsic significant advantage GTC possesses for near-diffraction-limited observations even compared to other large telescopes, and also the confluence of the technological and scientific horizons and the time lag of the GTCAO 1st-generation system compared to other large telescope adaptive optics systems.

A. Adaptive Optics Capabilities

1. Motivation

In assessing the competitive ability of the GTC in the modern era, perhaps the greatest "negative" factor for the observatory is that of timing/maturity – GTC is nearly the last of the 10-m-class telescopes, and the first such large telescopes (i.e. Keck) have been scientifically operational for more than 15 years. On the other hand, in diffraction-limited science cases, the observing time advantage provided by large telescopes scales not as D^2 (as for most seeing-limited cases), but in theory for sky background-dominated faint sources scales as D^4. The D^4 scaling provides a significantly larger advantage for the GTC in near-diffraction-limited science than in seeing-limited science – a relative 17% increase versus Keck and nearly x2.5 versus the 8-m telescopes for faint-source diffraction-limited targets[1]. This advantage is further enhanced by the fact that near-diffraction-limited instruments for large telescopes – mid-IR and adaptive optics (AO) assisted near-IR instruments – are still early in their life cycles. For this reason, even with the time lag of GTC compared to the other telescopes, CanariCam on the GTC should make an immediate scientific impact – it will provide 2.5x the speed and 25% higher angular resolution than its nearest competitors (T-ReCS and MICHELLE on Gemini, VIZIER on VLT). Thus, this scaling effectively breaks the "degeneracy" between 8-m-class and 10-m-class telescopes, placing the GTC and Keck telescopes in a class of their own, with significant performance advantages over 8-m-class telescopes for diffraction-limited science cases. For science cases that can take advantage of this

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[1] Note that the segmentation of the GTC, being quasi-filled-aperture in nature, does not have a major impact on the diffraction/sensitivity scaling for most scientific applications – the one possible exception being very-high-contrast imaging (i.e. Eikenberry, Shkedi, and Herter, 2003, SPIE, 4837, 776).

scaling, we can consider as the "competition" only Keck I and Keck II. Even for science cases where the target sizes exceed the diffraction limit of the GTC, but are still smaller than typical seeing conditions – for instance, many extra-galactic applications – the GTC will potentially provide significant competitive advantages over the 8-m-class telescopes beyond the usual D^2 scaling.

For reference, currently, the Keck telescopes' diffraction-limited capabilities include single-conjugate adaptive optics feeding several instruments:

- NIRC2 (a "workhorse" 1-5 μm imager and slit spectrograph)
- NIRSPEC (a single-slit medium- to high-resolution near-IR spectrograph)
- OSIRIS (a new, near-IR moderate-resolution integral field spectrograph)

The Keck system has received a significant boost from the addition of a Laser Guide Star (LGS) with OSIRIS, which increases the sky coverage from <1% to >80%. This has enabled vastly improved scientific breadth in adaptive optics observations – particularly in extra-galactic science (though also in Galactic cases as well). The number of corresponding AO-based scientific publications has more than doubled with Keck in the past year, and the expectation is that this trend will continue for some time as more scientists get the opportunity to use this recently-developed capability. The GTC is already moving along this path with GTCAO and FRIDA, which will together match the capabilities of the Keck system (assuming a prompt laser upgrade for GTCAO early in its life cycle).

With the deployment of GTCAO, the GTC project will have to invest in understanding the system and learn from it. This is not merely a technological matter of understanding a new instrument. The potentially complex interplay of the atmosphere, the telescope, the AO system, and the science instrument will likely pose a significant learning curve before full science benefits can be reaped. GTC must be prepared for this and engage the community in this challenging but rewarding endeavor. Future AO developments such as proposed in this section will have to build on the success of the GTCAO system.

2. Adaptive Optics Options

In the current era, there are many available new options for adaptive optics, as the field and its enabling technologies mature. Particular examples include wide-field near-diffraction-limited ("near-DL") approaches (i.e. Multi-Conjugate AO and Multi-Object AO), wide-field image sharpening (i.e. Ground-Layer AO), visible-wavelength AO, and high-contrast AO. While the Keck Next-Generation Adaptive Optics (NGAO) project is considering several of these options, it will likely only be able to pursue one or two of them. Thus, the GTC has the opportunity to take a leading role in some of the leading capabilities in a significant portion of the future adaptive optics parameter space. To better consider the alternatives, we briefly describe below four potential approaches to future adaptive optics with the GTC:

Ground-Layer AO (GLAO) – This approach to AO seeks to use image-sharpening correction to improve upon seeing-limited PSFs, providing FWHM ~0.3-arcsec over fields as large as tens of arcminutes on large telescopes. Scientifically speaking, this approach is as diverse and flexible as seeing-limited science, with the added advantages of ~x2 improved spatial resolution and ~x4 improved sensitivity (in terms of observing time for background-limited observations). GLAO systems are planned for Gemini-North and the VLT, using an array of imaging, multi-object spectroscopy, integral-field spectroscopy, and multiple deployable integral field unit ("multi-dIFU") spectroscopy instruments. However, because it is not diffraction-limited, GLAO only provides D^2 sensitivity enhancement of the GTC compared to other large telescopes (i.e. the same as for seeing-limited observation), forfeiting some of the potential advantages for the GTC. In addition, GLAO depends critically on the height of the turbulent ground layer at the telescope site, H, in that the solid angle of the GLAO-correctable field of view scales as ~$1/H^2$. On the other hand, GLAO is very scientifically diverse in its reach – the majority of seeing-limited scientific observations are possible (and improved) with GLAO.

High-contrast AO (HCAO) – As noted above, this approach may suffer the most from the segmented primary mirror of the GTC. While the total amount of light which is diffracted into "sidelobes" by the segmentation is small (~1%), it is large compared to the faint target intensities in high-contrast imaging. Thus, sidelobes of the brighter object can masquerade as, or even swamp, the primary PSF peak from the fainter targets. For this reason, the primary effort of the Keck AO community in high-contrast imaging – the Gemini Planet Imager (GPI), which is led by Lawrence Livermore National Laboratory and the University of California – is actually being implemented on the monolithic-mirror Gemini telescope.

Visible-light AO (VLAO) – This approach to AO seeks to extend near-diffraction-limited correction to the optical V-band (or shorter wavelengths) by using larger numbers and higher speeds of wavefront sensor pixels and deformable mirror actuators. This has all the usual advantages of observing in the most commonly-used (and in many senses, most scientifically sensitive/productive) bandpass in astronomy (as opposed to the less mature and sensitive observations typically available in the NIR or mid-infrared). However, VLAO is unproven and relies on dramatic (and as-yet unrealized) improvements in some of these technologies. For instance, the US National Science Foundation Roadmap Panel for Adaptive Optics recently (October 2007) concluded that VLAO is a high priority for significant national investment in necessary technology development simply in order to demonstrate its potential for scientific productivity.

Multi-Conjugate AO (MCAO) – MCAO is an approach to AO where (as its name implies) multiple deformable mirrors are optically-conjugated to different heights in the atmosphere corresponding to multiple turbulent layers. This approach (as opposed to the classical "Single Conjugate AO" or SCAO of most systems to-date) allows near-DL correction over much larger fields of view in the NIR band and (perhaps just as importantly) with stable/well-behaved point spread functions as a function of position within the corrected field. (Typical SCAO systems are notorious for producing PSFs which vary significantly across the field and with time, making accurate photometry or quantitative spectroscopy very difficult). This approach has been thoroughly simulated, and tested in laboratory environments, and over the year or two has seen several successful on-sky demonstrations with the MMT and VLT as a “proof of concept”. Most MCAO systems require multiple guide stars to tomographically probe the atmospheric turbulence above the telescope at any given instant and properly feed control signals to the deformable mirrors. Thus, current MCAO systems being developed either have very low sky coverage using multiple bright natural guide stars (i.e. MAD on VLT) or else will have reasonably high sky coverage using multiple laser guide stars (i.e. Canopus on Gemini) – though other approaches are being considered which could provide a balance between sky coverage and performance using only natural guide stars.

This approach provides an excellent combination of advantageous features for the GTC including:

- wide bandpass in a high-sensitivity wavelength range (~0.9-2.5 μm)
- correspondingly diverse/flexible scientific capabilities
- potential for D^4 scaling advantage for GTC.

With the latter, even though GTC will lag behind Gemini/VLT in implementation schedule, we can be uniquely powerful in resolution and sensitivity – an advantage further enhanced by the fact that both the Gemini/VLT systems will be operating in the Southern hemisphere. Also, given the great flexibility here, instrument choice can make further enhance uniqueness of GTC (see discussion below).

Based on the above, this committee focused on two of the options (MCAO and GLAO) for particular further study and analysis. We decided to drop HCAO from further consideration here because of the fundamental handicaps GTC’s segmented mirror may introduce to such a system’s performance. VLAO, while potentially very appealing, is currently perceived as a high-risk option. It will require significant technology development, as noted above, and as such even the approximate scientific performance (and thus potential benefits) of VLAO are currently very difficult to assess. Thus, while the GTC community should continue to monitor progress in VLAO technology, we award it a significantly lower priority for planning purposes.

In the subsections below, we present more detailed explorations of the MCAO and GLAO options in the context of future instrumentation for GTC.

3. MCAO & Potential Instruments

In the subsections below, we present a brief review of likely MCAO performance parameters on the GTC (III.A.3.a). We then provide a top-level description of drivers for potential MCAO instruments, along with recommendations for further study (III.A.3.b) including a multiple deployable IFU spectrograph. In subsection III.A.3.c, we describe the possible characteristics of such a spectrograph in more detail, along with two science programs to provide examples of the kinds of work that can be done with such a system.

a. Basic MCAO parameters

In Table 3 below, we present the expected typical full-system performance for a GTC MCAO system (based on the predicted performance of Canopus on Gemini). This assumes a laser guide star MCAO system with 3 fainter (R ~19 mag) natural guide stars for tip/tilt correction.

***Table 3** – MCAO expected system performance on GTC*

Parameter	**Value**	**Comment**
Image FWHM	Diffraction-limited (0.85-2.5 microns)	Full bandpass; true even for faint natural guide stars
Peak Strehl ratio	>60% (K) >40% (H) >20% (J) >3% (850nm)	At zenith Values decrease off-zenith (drop by ~x0.7 for K-band to ~x0.3 for J-band at 45-degree zenith angle)
Field of View (Strehl >0.5* peak value)	120-arcsec (H/K bands) 90-arcsec (J-band)	Gain in solid angle by ~x10-20 compared to SCAO systems
Field of View (stable PSF)	60x60-arcsec	Usable for precision photometry/spectroscopy
Sky Coverage	>70% (galactic latitude = 30°) ~15% (galactic pole)	

b. Science instrument possibilities

The MCAO system itself does not, of course, actually collect any scientific information – it simply provides corrected images for science instruments to analyze and record. Thus, the selection of science instruments for use with MCAO on the GTC will be a critical factor as well. “Workhorse” instruments for MCAO will fall into two broad categories: imaging and spectroscopy. Imaging with MCAO will be very scientifically useful and broad appeal (for instance, the first instrument for MCAO on both VLT and Gemini is an imager). On the other hand, in broadband imaging – even with MCAO correction – GTC will naturally suffer in terms of sensitivity (though not necessarily spatial resolution) in comparison to similar capabilities provided by space-based instruments such as JWST which may come on at this time. However, we note that the FRIDA instrument for GTCAO may be able to provide an imaging capability which is reasonably well-suited for MCAO on GTC, albeit subtending a slightly reduced field of view, with very little cost.

Meanwhile, spectroscopy – particularly integral field spectroscopy – can be a very powerful tool in conjunction with MCAO. This is especially true since such an instrument can have a true sensitivity boost over space-based instruments such as JWST in the NIR at moderate to high spectral resolutions. Since the primary benefit of MCAO over SCAO is the provision of a greatly-increased field of view, single-slit or even single-IFU spectrographs will be of little interest – again, the FRIDA instrument will already provide this capability with the 1st-generation GTCAO system, as does OSIRIS with Keck. However, multi-slit instruments will benefit from MCAO correction (for example, the FLAMINGOS-2 instrument on Gemini-South is designed to provide multi-slit spectroscopy in conjunction with the Canopus MCAO system). Even better yet would be a multi-deployable-IFU (multi-dIFU) instrument, providing multiplex gains combined with the spatial information/resolution at the diffraction limit enabled by MCAO.

Based on these considerations, we recommend studies of two potential instruments for MCAO with GTC. The first of these – a simple imager – could potentially be fulfilled by the current-generation FRIDA instrument, though a careful trade of the cost/benefit of a new MCAO-dedicated imager is definitely warranted. The second potential instrument – a multi-dIFU spectrograph – is described further below (Section III.B.3.c) along with some example science cases.

c. MCAO/Multi-dIFU Science Examples

The properties of the AO system and instrument needed will require detailed study well beyond the scope of this report. However, we can provide some approximate performance numbers based on studies and designs for MCAO systems on Gemini/VLT and IFU and multi-dIFU spectrographs for GTC (FRIDA) and TMT (IRMOS). These lead to the following parameters – primarily as an initial starting point for discussions

Table 4 *– MCAO/Multi-dIFU Basic Parameter Summary*

Parameter	**Value**	**Comment**
Wavelength	**0.8-2.5 µm**	Range of useful MCAO correction
Spectral resolution	**1,000-20,000**	Highest resolutions available only at finest pixel scales
Number of MOS probes	**~6**	Driven by balance between target density and cost/size
MOS patrol field	**2-arcmin diameter**	Range of useful MCAO correction
IFU field of view	**~2-arcsec diameter**	Smaller FOV for finer pixel scales
IFU field separation	**<1-arcsec min.**	Set by probe pickoff size
Slitlet widths	**25, 50, 100-milliarcseconds**	2-pixel widths matching 50% EED for various cases
Detector format	**2048x2048-pix**	HAWAII-2RG baseline
Instantaneous Wavelength Coverage	**Octave at low resolution; single atmospheric window at R~4,000**	
Sensitivity	**Sky background limited**	Detector noise becomes significant/limiting at higher resolutions

An instrument such as this has a very broad range of scientific applications, from galactic to extra-galactic. Detailed planning/description of these will be a critical task for future instrumentation, and also lies beyond the scope of this report. However, in order to give some idea of the range of science possible, we provide the following samples of scientific uses for an instrument with the properties described above.

i. Physics of the Bulge/Black-Hole Correlation in the Local Universe

Recent investigations have shown a remarkable correlation between the total mass (or velocity dispersion) of galactic bulges and the mass of the black holes which lay at the centers of these galaxies. Understanding this correlation is one of the key questions in the framework of galaxy formation and evolution. Little is yet known about the physical processes which lead to this relationship, but central ideas focus on gas transfer into and out of the central regions of galaxies (where the gravitational potential is the strongest), and the relationship of this gas flow to star formation. Basic unanswered questions are how black holes affect the star formation in galactic cores and how, in turn, star formation affects black hole growth. Galaxy mergers may play an important role in building up bulges and driving the growth of black holes early in their formation history. Thus, the star formation history within the inner parts of galaxies is thought to be a key to answering these questions, and can be probed through detailed abundance patterns in the oldest stars. These abundances carry elemental imprints from the earliest generations of stars. Importantly, GTC with an MCAO system and a multi-dIFU spectrograph can provide spatially-resolved spectra of individual stars in nearby galaxies. R=20,000 spectra in the H and K bands provide detailed abundance distributions of key elements, such as C, N O, Fe and many others, in red giant and supergiant stars. The alpha element ratios (abundances of Mg, Ti, Si, Ca compared to Fe) depend on the mass function of earlier generations of stars that have enriched the gas from which the observed stars have formed (Wheeler, Sneden & Truran 1989). The imprint of the earliest stars to form in the galaxy can thus be found. With the instrument/AO parameters presented above, GTC will be able to tackle observations such as this (and many other science cases relying on NIR spectroscopy of point-like targets in moderately dense regions) with unique power and sensitivity, realizing the full potential of its D^4 advantage.

ii. Galaxy properties at the epoch of peak star-formation (z ~1-3)

One of the flagship science drivers for current and future generation telescopes – including JWST, TMT, E-ELT, etc. – is the detailed study of galaxies in the era of peak star formation at redshifts $1<z<6$. This redshift range encompasses no more than the first ~30% of the age of the Universe, but may account for as much as ~70% of its total star formation, heavy element production, and black hole accretion (Madau & Shull 1996; Pei & Fall 1995; Pei et al. 1999). This is also widely believed to be a critical epoch in the emergence of massive galaxies. The redshift range $1<z<6$ has consequently become the focus of future major galaxy surveys aimed at understanding the physical processes that determine the formation of galaxies and their evolution into today's galaxy population (for instance, GOYA with GTC and OTELO with OSIRIS, among others). However, the empirical understanding of galaxy formation ultimately requires detailed mapping of the physical properties, including kinematics, metallicity, age, star formation rate, and extinction, *as a function of spatial position within each galaxy*. For each galaxy, observations with MCAO and a multi-dIFU spectrograph as described above will provide:

- *Star Formation Rate (SFR) maps:* via measurements of the H_α and [OII]3727 emission lines (Kennicut 1989).
- *Metallicity maps:* via measurements of the R_{23} ratio ([OII]3727 + [OIII]5007)/H_α (Edmuds & Pagel 1984), and [NII]/H_α ratio (Storchi-Bergman et al. 1994).
- *Extinction maps:* via the Balmer decrement (H_β/H_α) (Calzetti et al. 1994).
- *Dynamical masses:* via measurements of the internal velocity field, instead of a rotation curve or velocity widths (Vogt et al. 1997; Guzman et al. 1997; Erb et al. 2004).
- *Gas kinematics:* via emission line profiles and kinematical subcomponents to quantify the outflow/inflow of gas from/onto galaxies (Marlowe et al. 1994).

4. GLAO & Potential Instruments

In the subsections below, we present a brief review of GLAO likely performance and issues on the GTC (III.A.4.a). We then provide a top-level description of drivers for potential GLAO instruments, along with recommendations for further study (III.A.4.b). In subsection III.A.4.c, we summarize the kinds of work that can be done with such a system.

a. Basic approach/parameters

Ground-Layer Adaptive Optics (GLAO) aims to correct wavefront distortion due to ground layer turbulence only, while essentially ignoring turbulence at greater heights. The resulting AO correction does not typically produce near-diffraction-limited images, but simply achieves "image-sharpening" compared to seeing-limited PSFs. Rather than taking ~0.5-arcsec FWHM and turning it into ~50-mas FWHM diffraction-limited PSFs, GLAO would instead yield ~0.3-arcsec FWHM PSFs. However, the field over which the correction is achieved is relatively large compared to MCAO (for instance), even up to 10-arcminute diameters. For science cases where field-of-view is important rather than diffraction-limited angular resolution, GLAO can be an attractive option. An example is that of integral-field spectroscopy over moderately wide fields where in-slit energy is the defining factor for observing efficiency, or imaging and spectroscopy at very short near-IR and optical wavelengths where, as discussed for VLAO above, very high fidelity AO is not achievable with current day technology, but where GLAO can deliver much improved image sharpness with a comparatively stable PSF over the field.

GLAO has some technological advantages that might be of interest specifically to GTC. In particular, since only ground-layer turbulence is corrected only one deformable mirror is required. Moreover, in principle cheap, commercial laser technology can be used for (multiple) Rayleigh beacons, as has been demonstrated at the MMT. Furthermore, as noted earlier, the solid angle size of the correctable field of view for GLAO varies inversely as the square of the scale height of this ground layer. Since GLAO does not produce diffraction-limited images, GTC only has a D^2 advantage compared to other telescopes. Recent measurements at Mauna Kea indicate turbulent scale heights as low as <300m, so this parameter needs to be similar (<400m) for GTC to maintain a competitive advantage over the Gemini-North telescope and its GLAO system. Thus, in order to properly assess the utility of GLAO for GTC, it will be critical to obtain high-resolution (<100-m) measurements of the ground layer turbulence structure at the GTC site.

b. Science instruments for GLAO

i. Possible use of existing instruments

One potentially very attractive option for science instrumentation with GLAO is the use of already-existent GTC instrumentation, at little/no additional cost beyond the GLAO system itself. As noted several times, GLAO essentially enables the same observations as in the seeing limit, but with slightly sharper PSFs (as opposed to other AO approaches which produce much tighter near-diffraction-limited PSFs over a much more limited field of view), and therefore improved sensitivity. Thus, to first order, any seeing-limited instrument for GTC would also serve for GLAO observations, as long as the pixel scale is small enough to properly sample the GLAO-delivered PSFs. If we assume that GLAO will deliver ~0.2-arcsec and larger FWHM under good observing conditions in the NIR and ~0.3-arcsec and larger FWHM in the optical, then instruments with pixel scales of ~0.10-arcsec (NIR) and ~0.15-arcsec (optical) will suffice. Thus, both CIRCE (0.10-arcsec/pixel) for the NIR and OSIRIS (0.125-arcsec/pixel) for the optical should be directly compatible with a GLAO system. Furthermore, OSIRIS can also provide multi-object spectroscopic and tunable-filter imaging capabilities for GLAO. It is possible that with appropriate optics schemes, EMIR could also be exploited with GLAO to provide multi-object NIR spectroscopic capabilities.

Thus, we can at least imagine that a very powerful instrumentation suite for GLAO could be provided at low cost from existing GTC instrumentation. The primary drawback of this approach is that it may not be able to take full advantage of the corrected GLAO field-of-view. And, as noted above, without taking that advantage, GTC runs the risk of losing the competitive edge provided by its superior aperture. In short, if either the GLAO-correctable field or the instrumental field of view is significantly smaller than ~8-arcmin diameter, GTC risks being at a sensitivity disadvantage compared to the Gemini-North 8-meter with a ~10-arcmin GLAO-corrected FOV. Thus, we can see that while the existing GTC instrumentation can certainly provide some initial benefit from GLAO implementation on GTC, to seek full advantage we would need instruments specially developed for GLAO.

ii. Possible future instruments

The range of optical/NIR instruments suitable for use with GLAO is as broad and diverse as those which can be considered for seeing-limited observations – from imagers to spectrographs, from polarimeters to multi-dIFU spectrographs, and so on. The critical features of any such instruments will be suitable pixel scales (i.e. ~0.10-0.15-arcsec/pixel) and efficient use of a full GLAO-corrected field of view of ~10-arcminute diameter. Logical high priority instruments could include optical/NIR imagers covering the GLAO full field, multi-object slit spectrographs, and/or multi-dIFU spectrographs in the optical/NIR. We mention here as an example the development of MUSE on the VLT, which will exploit massive integral-field spectroscopic multiplexing capability in the optical over a 1-arcminute field at a resolution of 0.2 arcsec.

Selecting among these options will of course depend on the expected GLAO PSF FWHM, FOV, etc. in the context of science drivers developed by the community, as well as trades of cost/benefit in light of the possibility of using existing GTC instruments in a (potentially) more limited manner.

c. Science cases for GLAO

As stated above, virtually any science case for seeing-limited observations which would benefit from sharper image PSFs would improve via the use of GLAO correction. One example would be spectroscopic studies of high-z galaxy populations. As a consequence of the relatively low number density of high-z galaxies, these studies require multi-object (or multi-IFU) observations over a large (patrol) field of view to take full advantage of the multiplexing gain. An improvement in the image quality implies a direct gain in sensitivity, which translates to moving down along the luminosity function and/or towards larger redshifts. Other examples would include studies requiring near infrared imaging of nearby galaxies (including, for instance, monitoring for SN searches), stellar population studies (imaging or spectroscopic) in crowded fields in the Galaxy and nearby galaxies (i.e. center of M31 and NGC 604 in M33), and many, many others.

B. Other Instruments/Capabilities

As described above, GTC is expected to have good and complete coverage of the instrumental parameter space for the optical to mid-IR by 2013, and we just mentioned above several relevant niches we think GTC should concentrate on by 2018 and beyond. It is then difficult to recommend further very specific instruments or capabilities for GTC for this Mid-Term era. Nevertheless, GTC should be quite aware of scientific and technology advances over the next 5 years, since these will lead to new and unique science programs which in turn motivate exciting new instrumentation. Among areas discussed by this Working Group as meriting special attention are:

1. Multiplexing. In the near future, it will become more common, possible and affordable to conceive instruments, groups of instruments and/or detectors for higher-multiplex observations (doing more than one thing at a time, like simultaneously covering different energy regimes, resolutions, observing modes, etc).
2. Quasi-simultaneous multi-mode. Similar to multiplexing, but not quite the same, is the potential to increase the ability to switch as quickly as possible between observing capabilities, to allow for an almost simultaneous measurement of several properties of a given object (e.g. imaging, spectroscopy, polarimetry, etc) as well as for a fast and proper response to observe relevant targets of opportunity.
3. Follow up of many other technical advances is of relevance too (fiber optics, lucky imaging, micro remote controlled mechanisms, special optical devices and detectors, micro/macro optics, coatings, etc.)
4. Changes in scientific focus. It is common that new findings and developments give known techniques or scientific areas new impulses. Radial velocity or transit studies for planet findings may be cited as a recent example. A possible

future field, among others, might be the study of magnetic fields through polarimetric measurements.

It is clear that GTC needs to be ready to jump on these yet-unknown opportunities. One possibility is that GTC prepares a specific fund for this, but it will be difficult to properly plan and quantify it. More realistically and practical for GTC is to define an aggressive program to attract visitor-type instruments, developed by groups and funds beyond the GTC observatory itself, to be the first to attract these first-of-class instruments.

C. Timeline/budget

In order to have the above-recommended instruments/capabilities operational at the telescope by 2018, their definition and development should begin very soon. Timing-wise, the earliest order of business will be a site characterization study with high altitude-resolution to determine the likely performance of GLAO at the GTC site. This study should be initiated as early as possible in 2009 and strive for completion by early 2010. Beginning in 2010, the GTC will need to initiate feasibility studies for both MCAO and GLAO possibilities for the GTC. These studies should include AO system and performance modeling, science cases, instruments (including performance and priorities), and cost/risk analyses. In the year 2011, the selected system(s) should begin conceptual design studies to be completed in 2012. Full design phase will need to begin in 2013 in order to have the first of the Mid-Future instruments on-sky by the stated goal date of 2018.

At this early juncture, it is extremely difficult to provide any more than rough order-of-magnitude cost estimates for the instruments/capabilities we have identified above. However, we estimate that the cost of the MCAO system may be ~8-10 million Euros (excluding backend scientific instruments), plus an additional cost of ~3 million Euros for a laser guide star system. A multi-dIFU spectrograph would have an estimated cost of approximately 13-16 million Euros (assuming 6 IFU/spectrographs at an average cost of 2-2.5 million Euros each and about 1 million Euros for a deployable pickoff interface). we estimate that the cost of the GLAO system may be ~6-8 million Euros (excluding backend scientific instruments), based on the Gemini GLAO feasibility study.

D. Summary of Mid-Future (2018+) Recommendations

We present here a brief summary of the key points and recommendations of the analyses for the Mid-Future term (i.e. capabilities that will be coming on-sky beginning around 2018):

- GTC should promote the development of science cases from the community and initiate feasibility studies for Multi-Conjugate Adaptive Optics capabilities, and related instrumentation capabilities, as described above. In order for these capabilities to come on-sky near 2018, feasibility studies should begin no later than early 2010.
- GTC should promote the development of science cases from the community and initiate feasibility studies for Ground Layer Adaptive Optics capabilities, and related instrumentation capabilities, as described above. In order for these capabilities to come on-sky near 2018, feasibility studies should begin no later than early 2010. Because GLAO performance is closely tied to the currently-unknown ground layer turbulence scale height at ORM, GTC should commission a study to provide high-resolution measurements of the ground layer properties in 2009.
- GTC should expect to develop additional instrumentation capabilities over this term. The details of the critical scientific performance characteristics of such instruments will emerge over the next few years in terms of both scientific and technological advances, and we have described some of the most likely focus areas above.

IV. Far Future (2023+)

Far future (2023+) GTC instrumentation will be determined by scientific and technological advances over the next 10-15 years. This is of course largely unknown. At that time JWST and ALMA are expected to be mature facilities, and giant ground based telescopes like E-ELT and TMT should already have been in operation for a number of years. These facilities are expected to change science's course and priorities, making fundamental breakthroughs in several fields.

While the prediction of science (and required instrumentation needs) at these long temporal scales is a very uncertain exercise, we have identify the following technological areas for which the GTC community should monitor progress closely.

- **Visible Light AO**: This seems a natural extension of current and mid-term planned AO developments for the next decade or so, in any case. Judging from developments at other large telescopes and the important technological advances that are under way, we do foresee that adaptive optics will continue to grow in importance for future novel astronomical instrumentation. GTC should therefore keep abreast with these developments.

- **Detector technologies**: Detectors (from naked eye to modern devices) have guided the progress of astronomy in the past and, they will likely guide its future as well. Although developments in this broad field are to some extent unpredictable, and involve a community much larger that the astronomical one, the GTC project should be ready to evaluate the potential of the different alternatives that may arise.

Further revisions of the present document (which we suggest to be carried out with a recurrence period no larger than five years, or so) will allow the GTC community to update and specify the areas for future developments in the 2023+ epoch.

In any case, and despite of all the uncertainty predicting future, we can just suggest approaches to take full advantage of an evolving scientific and technological environment. Readiness to consider new instrument concepts and technologies, strong involvement in the decision-making process of the community to which GTC ultimately serves, and a clear competitive scheme in the selection processes are all key elements to guarantee a successful future for GTC instrumentation.

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Gran Telescopio de Canarias, S.A.

Instituto de Astrofísica de Canarias
Vía Láctea s/n
38200 - LA LAGUNA, TENERIFE, Islas Canarias
Tfno +34 922 315 031 Fax +34 922 315 032

Centro Común de Astrofísica de La Palma
Cuesta de San José s/n
38712 BREÑA BAJA, LA PALMA, Islas Canarias
Tfno +34 922 425 720 Fax +34 922 425 701

http://www.gtc.iac.es E-Mail: gtc@iac.es

Received by	Pedro Alvarez Project Director	Signed in the original copy
Authorized by	Pedro Alvarez Project Director **Date:**	Signed in the original copy **28/08/08**

Report of the Gran Telescopio Canarias Future Instrumentation Working Group

Stephen Eikenberry (Chair)
Santiago Arribas
Jesús González
Artemio Herrero
René Rutten

02 May 2008

Contents

Executive Summary

The primary purpose of this report is to provide guidance to the Project Office and offer a basis for future discussion within the scientific user community of the Gran Telescopio Canarias (GTC) regarding priorities for future instrumentation. The GTC Project Office commissioned the Future Instrumentation Working Group to investigate instrument complements needed in the future in order to optimize the scientific productivity of the GTC, in the context of the scientific drivers from the GTC community, observing capabilities available to the community, and competing capabilities around the world. The Working Group subdivided the "future" into: the "Near-Future" (priorities from the current era to 2013 or beyond), the "Mid-Future" (priorities for 2018 and beyond), and the "Far Future" (2023 and beyond). The Working Group expects that a similar process to review, re-assess, and re-establish priorities should take place approximately every 5 years (or more frequently if the community so determines).

For the Near-Future term, the key recommendations of this Working Group are the following:

1. GTC should develop a medium-resolution (R > 10,000) optical multi-object spectrograph for on-sky commissioning in 2013. The estimated total cost of this project is 8-10 million Euros (including manpower).
2. GTC should develop a medium-resolution (R > 10,000) near-infrared multi-object spectrograph for on-sky commissioning in 2013. The estimated total cost of this project is 8-10 million Euros (including manpower).
3. Queue-scheduled observations will be critical to optimizing the scientific return of the GTC, and should be fully supported.
4. Visitor or "PI" instruments provide an important contribution to the potential scientific flexibility and productivity of the GTC, and the GTC should develop clear guidelines for working with such instruments.
5. The high-resolution portion of the proposed SIDE instrument would seem to fulfill the requirements for the medium-resolution optical spectrograph. The low-resolution and infrared portions of the SIDE instrument would not seem to contribute directly to the merit criteria we have established here.
6. GTC should commission a study as soon as possible to assess the suitability of the UES instrument for meeting the scientific needs of the GTC community in the area of high-resolution optical spectroscopy, as well as possible alternative plans for this capability.

For the Mid-Future term, the key recommendations of this Working Group are the following:

7. GTC should promote the development of science cases from the community and initiate feasibility studies for Multi-Conjugate Adaptive Optics capabilities, and related instrumentation capabilities, beginning no later than early 2010.
8. GTC should promote the development of science cases from the community and initiate feasibility studies for Ground Layer Adaptive Optics capabilities, and related instrumentation capabilities, beginning no later than early 2010. Because GLAO performance is closely tied to ground layer turbulence scale height at ORM, GTC should commission a study to provide high-resolution measurements of the ground layer properties in 2009.
9. GTC should expect to develop additional instrumentation capabilities over this term. The details of the critical scientific performance characteristics of such instruments will emerge over the next few years in terms of both scientific and technological advances.

Finally, in the Far-Future term, GTC will need to be open to fundamentally re-assessing its direction and mission in a time of multiple ground-based ELTs and a mature JWST space-based facility.

I. Introduction/Motivation

A. Scope of This Report

The primary purpose of this report is to provide guidance to the Project Office and offer a basis for future discussion within the scientific user community of the Gran Telescopio Canarias regarding priorities for future instrumentation. The GTC Project Office commissioned the Future Instrumentation Working Group to investigate instrument complements needed in the future in order to optimize the scientific productivity of the GTC, in the context of: (a) the scientific drivers from the GTC community; (b) observing capabilities available to the community; (c) competing capabilities around the world. The Working Group subdivided the "future", for the purposes of this report, into three separate time ranges: the "Near-Future" (encompassing priorities for capabilities from the current moment to those which should come on line in 2013 or beyond), the "Mid-Future" (encompassing priorities for capabilities which should come on line in 2018 and beyond), and the "Far Future" (encompassing priorities for capabilities which should come on line in 2023 and beyond). The Working Group expects that a similar process to review, re-assess, and re-establish priorities should take place approximately every 5 years after iteration based on community interests (or more frequently, if desired).

The fundamental mindset of the Working Group was to take the interests of the full range of the GTC partnership to heart. We acknowledge that a full determination of detailed priorities for and specifications of instrumentation clearly requires the participation of a broader swath of the GTC community than can possibly interact properly in a small committee environment such as this. In addition, we note that the GTC is multi-national, and no specific "national strategic plan" for astronomy was available to help define/guide our efforts. For similar reasons, the Working Group did not have access to any well—defined statement of expected funding levels or even funding sources for future instrumentation for GTC.

Accordingly, rather than attempt to define particulars of instrument selection and specifications, we instead chose to focus our energies on investigating and refining broad areas and directions for future GTC instrument development. Determination of specific instrument requirements and features will require further study and definition by GTC scientific community and, together with feedback on constraints of available funding, balanced to provide the optimal scientific return for the observatory as a whole.

In the remainder of this section, we review the necessary background and contextual information needed to begin consideration of the future instrumentation priorities of the GTC. In Section II, we present considerations for instrumentation priorities in the Near-Future (2013+) term. In Section III, we present considerations for instrumentation priorities in the Mid-Future (2018+) term. Finally, in Section IV, we present a brief discussion of likely considerations for GTC instrumentation in the Far-Future (2023+) term.

B. Background/Context Information

As noted above, key issues for determining the optimal set of future instrument priorities on the GTC are the current observing capabilities available to the GTC community, as well as the current and envisioned competing capabilities around the world. In Subsection I.B.1 below, we provide a brief review of the GTC instrumentation suite currently under development which we take as the "existing baseline" capabilities. In Subsection I.B.2, we present a listing of current observatories and/or surveys available for use in a broader worldwide-community sense – a detailed summary of the capabilities of each is well beyond the scope of this report, but this list should provide some indication of the facilities we considered during the preparation of this report. In Subsection I.B.3, we present a similar list of future observatories which will be part of the GTC scientific context in the coming decade.

1. "Current" GTC Instruments

We begin with a brief review of "current" instrumentation for the GTC, as defined by the GTC Project Office. We note that for consistency's sake this list includes only the instruments which have been approved for construction and installation on the GTC at the time of this report.

a. OSIRIS

OSIRIS is a powerful multi-purpose workhorse instrument for the GTC operating in the optical waveband (0.36-1.0 µm). OSIRIS was specifically designed for narrow-band tunable-filter imaging, -- a uniquely competitive general-science niche among 8m to 10m-class telescopes. OSIRIS also provides a very full set of other observational modes, including long-slit and multi-object spectroscopy (R<~ 5000), fast photometry and spectroscopy, as well as powerful CCD-transfer/telescope-nodding/tunable-filter combination modes. It covers a significant portion of the unvignetted GTC field of view with a proper oversampling of good seeing ORM conditions. Narrow-band imaging can be continuously tuned from 365 to 1000 nm (FWHM from 12 to 40 Å). Spectroscopically, it samples $R = \lambda/\Delta\lambda$ resolutions from 300 to ~5000 (0.6" slit width), and in MOS mode can accommodate from 40 to several hundred object spectra in fields that depend somewhat on the chosen resolution.

Given the plate scale (~0.125 arcsecs/pixel) which was optimized for imaging, the OSIRIS spectroscopy mode is somewhat oversampled, which is not a bad feature per se but, counting on "only" 4102 pixels along the dispersion, the one-octave wavelength coverage is limited to resolutions R~1000. Nevertheless, for the very competitive R=2500 spectral resolution OSIRIS provides enough highly-efficient grisms to cover the whole optical range in four wavelength intervals. The highest R=5000 resolution, at the moment is available only in the red ($0.8 \leq \lambda[\mu m] \leq 0.93$), but specific science programs could purchase other R=5000 grisms as required. In spectroscopy OSIRIS also delivers a competitive field of view, considerably larger than similar instruments of its class, like GMOS (Gemini) and LRES (Keck), but naturally delivering a smaller spectroscopic field than much larger (and significantly more expensive) wide-field MOS spectrographs such as DEIMOS (Keck) & VIMOS (VLT).

The instrument throughput is remarkably competitive. Its optical transmission (excluding dispersive elements and detector) is significantly better at all wavelengths than similar instruments like FORS (VLT), GMOS (GEMINI), and LRIS (Keck). Overall, OSIRIS is a competitive instrument in its class, with the extra advantage of tunable imaging, making it quite a competitive and adaptable workhorse optical instrument for broad and narrow band imaging and low-to-intermediate (R<~5000) spectroscopy.

b. CanariCam

CanariCam is the second “first light” instrument for GTC, and will serve as the facility mid-infrared instrument. CanariCam has four science modes and two engineering modes, which use the same 320 × 240-pixel, arsenic-doped silicon, blocked-impurity-band detector from Raytheon. CanariCam represents an evolution of the successful instrument design of T-ReCS, the Gemini South facility mid-IR imager/spectrometer commissioned in summer 2003, which was also designed and built at the University of Florida. Each mode can be remotely selected quickly during an observing sequence. The pixel scale is 0.08 arcsec, resulting in Nyquist sampling of the diffraction-limited point-spread-function at 8 microns, the shortest wavelength for which CanariCam is optimized. The total available field of view for imaging is 26 arcsec × 19 arcsec. The primary science mode will be diffraction-limited imaging using one of several available spectral filters in the 10μm (around 7.5-13.5 μm) and 20 μm (around 16-26 μm) atmospheric windows. Any one of four plane gratings can be inserted for low and moderate-resolution (R = 60 - 1300) slit spectroscopy in the 10 and 20-μm regions. In the 10 μm window, insertion of appropriate field and Lyot stops converts the camera into a coronagraph, while insertion of an internal rotating half-wave plate, a field mask, and a Wollaston prism converts the camera into a dual-beam polarimeter.

c. EMIR

EMIR is the facility wide-field near-infrared (NIR) imager and multi-object spectrograph for the GTC. EMIR provides a 6x6-arcmin imaging FOV, with broadband filters covering the 0.9-2.5-micron wavelength range. It also uses a cryogenic configurable slit unit for multi-object spectroscopy of up to ~50 targets simultaneously over a 6x4-acrmin field of view. Spectroscopic resolution provided by pseudo-grism dispersers range from R ~5,000 in the K-band to R ~4,000 in the J-band. EMIR is a general-purpose instrument, with a wide range of capabilities, and a design optimized for multi-object spectroscopy of high-redshift galaxies in the K-band.

d. CIRCE

The Canarias InfraRed Camera Experiment (CIRCE) is a near-first-light near-infrared (1-2.5 micron) instrument. While the EMIR instrument is scheduled to come on-line for GTC sometime after first light, CIRCE will be the only NIR instrument available for GTC for its first period of operation, and will thus fill a crucial gap in “first-light" instrumentation between the other facility instruments: OSIRIS and CanariCam. In addition, the optics and detector array of CIRCE will provide a pixel scale (0.10 arcsec/pixel) fine enough to properly sample the excellent images provided by GTC, while at the same time providing a near-IR field-of-view (3.4x3.4-arcmin) comparable to any currently available on the world's large telescopes (areal FOV ~25 times larger than NIRC on Keck, and ~3 times larger than NIRI on Gemini). In addition, after the delivery of EMIR, CIRCE will continue in scientific use on the GTC Bent Cassegrain “visitor" ports, where its high image quality and resolution, polarimetric capability, high time-resolution readout, and lower spectral resolution (useful for very faint targets) will complement the capabilities of EMIR and continue to augment the scientific capabilities of one of the world's largest optical/infrared telescopes.

e. FRIDA/GTC-AO

FRIDA and the GTC Adaptive Optics systems (GTC-AO) will provide near-diffraction-limited imaging and integral field spectroscopy over the 0.9-2.5-micron bandpass on the GTC. GTCAO will initially provide natural-guide-star correction over the isoplanatic patch with Strehl ratios as high as ~65% in the K-band. A planned upgrade of GTCAO will provide a laser guide star with similar Strehl ratio and dramatically improved sky coverage. FRIDA has two main science pixel scales of 10-mas/pixel and 20-mas/pixel, allowing adequate/good sampling of the diffraction-limited PSF over the JHK bandpass with fields of view exceeding the expected isoplanatic patch size. In addition, FRIDA will have integral field spectroscopic capabilities using an image slicer with 3 selectable spaxel scales and fields of view matched to various science cases and resolutions from R ~1,000 up to R~30,000.

2. Other observatories now

a. 8-m to 10-m observatories

***Table 1** – The following table summarizes the main present-day large optical and infrared observatories.*

Facility	Aperture (m)	Observatory	Partners
LBT	11.3 2x8.4	Mt. Graham, Arizona USA	Arizona, Italy, Germany, Ohio State U., Research Corporation. (OSU, NDU, UMin, UVir)
GTC	10.4	ORM, La Palma Spain	Spain, México & U. Florida
Keck I & II	2 x 10.0	Mauna Kea, Hawaii USA	Caltech, U. California, NASA
SALT	9.8	Northern Cape, S. Africa	S. Africa, HET, Poland, India, UKSC, Göttingen & several USA universities.
HET	9.2	Mt. Fowlkes, Texas USA	U Texas, Penn State, Stanford, Munich (LMU), Göttingen (GAU)
Subaru	8.3	Mauna Kea, Hawaii USA	National Astronomical Observatory of Japan
VLT	4 x 8.2	Cerro Paranal, Chile	European Southern Observatory (ESO)
GEMINI-N	8.1	Mauna Kea, Hawaii USA	USA, UK, Canada, Australia, Argentina, Brazil & Chile
GEMINI-S	8.1	Cerro Pachón, Chile	
Magellan	2 x 6.5	Las Campanas, Chile	Carnegie, U. Arizona, Harvard/CfA, U. Michigan, MIT
MMT	6.5	Mt. Hopkins, Arizona USA	Harvard/CfA, U. Arizona

It is clear that the most powerful astronomical countries and institutions have either developed or have access to large aperture observatories. Most of these consortia are highly capable of operating their facilities and developing competitive and up to date instrumentation, so it will not be an easy task for GTC to excel among them. GTC can only be competitive with a proper combination of its slightly-larger aperture with a set of carefully chosen instruments and telescope capabilities matched to the properties, strengths and growing plans of its particular scientific community. Among all these observatories the ESO/VLT is particularly important for defining the context for the second generation of GTC instruments, and several specific references to its individual instruments will be made later in the report.

b. Wide-field surveys (i.e. Sloan, Vista, LSST, PAN-STARRS)

One of the possible drivers for future GTC instrumentation is to take advantage of current and planned large surveys. These could lead to the design of instruments particularly well-suited for the follow-up of such surveys. Due to its relatively limited field-of-view (FOV) GTC is not well-optimized for large-scale surveys – the "A" advantage GTC enjoys in area can be overcome by the "Ω" advantage of other smaller telescope. Thus, surveys with GTC should concentrate on depth and probably specialize in narrow-band filters and spectroscopy.

For our purposes, the primary surveys of interest would be ending around 2011-12 (end of first-generation instrument construction and beginning of the second generation) and around 2017 (end of second-generation instrument construction). Below we give some numbers for the largest ground-based surveys, either finished, ongoing or planned. For a full discussion, space-based surveys like GAIA, which should extend up to 2020, should be added to the list.

Table 2 – Ground-based surveys. This list, including the largest planned (or nearly finished) surveys, is provided to orient the reader. Most data have been extracted from the official web pages or from conversations with scientists closely related to the projects.

	LSST	Pan-Starrs	UKIDSS	VHS	VIKING	IPHAS	DES	SDSS I+II
Wavelength	Visible	Visible	NIR	NIR	Red-NIR	red	red	Visible
Area (deg^2)	20000	30000	7500	20000	1500	1800	5000	8000
Hemisphere	South	North	North	South	South	North	South	North
Begin	2014	2010	2005	2010	2010	2003	2010	2002
End	2019		2012	2015	2015	2008	2015	2008

The surveys closest to the 2017 date are the Pan-Starrs and LSST surveys (Pan-Starrs has no completion date, but it can be estimated to reach a depth comparable to LSST). LSST is in the South and will share with GTC a band of ±20 degrees (or slightly more) around the celestial equator, while Pan-Starrs will nearly overlap in sky coverage with GTC. Both share sufficient sky with GTC to be considered interesting. The Dark Energy

Survey (DES) is still trying to get the required funds (although there are good prospects for doing so). Planned for a 5-year duration, the expectation is that it will be finished slightly before 2017 (present schedule is 2010-2015). Again, making use of the Victor M. Blanco 4m telescope (CTIO) the sky overlap with GTC will be limited as LSST. The same situation arises with the planned VISTA and (more uncertain) VST surveys – expected to end about 2015 and limited sky overlap with GTC (although a bit more than LSST and DES). Another interesting survey is UKIDSS, which will be finished by 2012 and from which there have already been three data releases.

Surveys such as SDSS I and II or IPHAS can also be considered, but they should not drive future GTC instrumentation as strongly, as their exploitation is currently underway. OSIRIS and EMIR are adequate for follow-up spectroscopy of objects detected in these surveys. Surveys like Alhambra or OTELO have a special interest because they are rooted in the GTC community, but they have a much smaller field than others considered here. They can, however, be very efficient users of GTC instrumentation and should be taken into account when deciding about observing modes of planned instruments, but again should not drive future GTC instrumentation (with the possible exception that the involved teams want to propose instrument projects dedicated to that purpose).

Therefore the ground-based surveys that are most relevant for the context of GTC future instrumentation are LSST, Pan-Starrs, UKIDSS and DES. UKIDSS will be finished relatively early, so that its interest could be limited to some specific aspects (f.e., a subsample of objects with given characteristics). DES and LSST surveys may also be advantageous, but the large 8m telescope in the South will be in better position to take advantage of them. Finally, surveys rooted in the GTC community may use general purpose instrumentation and even influence it. However, dedicated instrumentation, although interesting, should be considered with caution in view of the limited resources available (foci, observing time, budget, manpower). The effort in such cases should rely more in the interested groups.

c. *Space (HST, Spitzer, etc.)*

The successful synergy between Hubble Space Telescope (HST) and Keck and VLT is expected to be extended in the future to GTC too. This will be especially true if the ambitious SM4 (Servicing Mission Four) plan to refurnish HST is completed. Under this assumption, HST's operational life will be extended by at least five years, and its imaging capabilities will be boosted by the installation of WFC3 (and the recovery of the ACS). As a generic rule of thumb, deep spectroscopic observations in the optical and near-infrared wavelengths with ground-based 8- to 10-m-class telescopes and high angular resolution HST imaging nicely complement each other for many studies (e.g. high-z galaxy population studies). On the other hand, the installation of the Cosmic Origins Spectrograph (COS) on HST will provide UV observations with unprecedented sensitivity in the 1150-3200Å spectral range – a region inaccessible from the ground. The opening of this new window will certainly require complementary spectroscopic observations in optical and near infrared, which are most efficiently obtained from the ground. In summary, complementarity with HST calls for efficient optical and near-infrared spectrographs for GTC.

Despite its small aperture, Spitzer provides full access to the spectral range 3 - 180 microns with unprecedented sensitivities. Ground based 10-m-class telescopes cannot compete in terms of sensitivity with Spitzer in the mid-IR (even in the N band with diffraction limited observations) as a consequence of the high level of background produced by the atmosphere at these wavelengths. This disadvantage is even more dramatic in the Q band, where the atmosphere shows high variability. GTC should provide complementary capabilities, mainly in the optical and near infrared (up to 2.5 microns) spectral range with both imaging and spectroscopic observations. However, in terms of angular resolution, GTC mid-infrared observations have the potential to greatly improve the relatively poor angular resolution provided by Spitzer at these wavelengths, even for seeing-limited observations. Obviously optical/near-infrared GTC instruments will provide angular resolutions much better than those reachable with Spitzer, specially if they are assisted by AO systems.

There are many other current astronomy space missions such as XMM-Newton, INTEGRAL, SWIFT, and CoRoT. Although complementarities among all these facilities are expected for some studies, they are well served by planned GTC instrumentation and the proposed medium-resolution optical spectrograph.

3. Other observatories in the future

The future context for GTC instrumentation will of course include all of the facilities listed in I.B.2 above. In addition, we note four broad categories of new future capabilities which will be coming on-line during the timescale considered for this report. These include Extremely Large Telescopes (ELTs), the James Webb Space Telescope (JWST), the Atacama Large Millimeter Array (ALMA), and a broad category of “other future space missions”. We briefly describe each of these below.

a. ELTs

One of the most obvious areas where future observatories will impact the GTC will be the advent of the “Extremely Large Telescopes”. Much as Keck, the 8-meter telescopes, and now GTC are revolutionizing the astronomical world previously dominated by 4-meter and 5-meter telescope, the ELTs – with apertures from 20-m to 42-m in diameter – will re-define the astronomical world of the future. The leading projects envisioned now include the Giant Magellan Telescope (GMT – 20-m diameter), the Thirty Meter Telescope (TMT – 30-m diameter), and the European ELT (E-ELT – 42-m diameter). These observatories will include a broad range of scientific capabilities, running the gamut from optical seeing-limited observations to diffraction-limited observations in the near- and mid-infrared wavebands. While the first light capabilities – coming on-line in the next 5-10 years – may be initially somewhat limited by instrument choices, we can assume that in the long-term (i.e. 2020 and beyond) these telescope will have a similar suite of instruments to match those of the current generation of large telescopes.

b. JWST

JWST will serve the international community at large (similarly to HST), and is also expected to make fundamental breakthroughs in many fields of Astronomy. According to the current schedule JWST will be launched during mid-2013, and will be operational for 5/10 years (requirement/goal). Therefore, the timeframe for JWST fits well with that considered for a second generation of GTC instruments.

Unique capabilities of JWST over ground optical/infrared telescopes are:

- Sensitivity: JWST imaging is unique in terms of sensitivity beyond 1.7 microns even for a 30m telescope in imaging and low/moderate-resolution spectroscopy (e.g. Science Assessment Team, 2005).
- Continuous spectral coverage from 0.6 to 28µm,
- Good and stable PSF over a wide FoV, with diffraction limited observations for $\lambda > 1.7$ µm.

It is expected that GTC, like other major ground-based telescopes, will complement JWST observations. The following are complementary areas for GTC:

- High spectral resolution (>3000) spectroscopy. JWST lacks this capability.
- UV-Visible accessibility below 0.6 microns. This spectral range is not covered by JWST. This will be particularly important after HST is decommissioned.
- GTC+AO has higher spatial resolution than JWST. In the mid infrared, under good seeing conditions GTC will approach the diffraction limit, which is also higher than JWST.
- Accessibility to a larger FoV. JWST imaging and spectroscopic (MOS) instruments have few arcminute squared FoV (i.e. ≤ 3' x 3'), while GTC could take advantage of substantially larger values.
- Multi-IFU observations. This capability is not provided by JWST.
- Flexible time allocation. Important for targets of opportunity.
- Upgradeable and versatile. GTC (ground) should take full advantage with respect to the less flexible space facilities to improve and adapt its instrumentation.

The different nature of these two telescopes, and the fact that they serve to quite different communities does not recommend to guide the GTC instrumentation by the list above. However, such a list may provide additional information when different GTC instrument options are considered.

c. ALMA and LMT

ALMA is the ultimate observatory for the millimeter and sub-millimeter spectral region. Its construction is properly advancing and it will be in operation well in time to complete the set of next generation observatories (together with JWST, the optical/IR ELTs, the EVLA and the rest of main space missions). There is no other facility of its kind planned for the foreseen future, and it is therefore a well-coordinated international effort among all main astronomical world powers (ESO, North America and Japan, among others). Naturally, GTC is in fact considered a part of the synergistic and follow-up facilities for ALMA.

The main ALMA science driver is the unique observation of the cold universe, which includes the detection of a large number of newly-discovered galaxies particularly at high redshifts ($z>1.5$). GTC will not be the optimal telescope for ALMA follow-up surveys, but certainly a great tool to study selected ALMA samples and their environment, mostly through NIR spectroscopy and narrow- and broad-band imaging in the optical, NIR and mid-IR. For galactic objects, GTC could help with AO observations of the closest cold objects detected, before the ELTs become fully operational.

Since the main GTC partnership is involved in the ALMA project, the GTC future instrumentation already has ALMA as an integral part of its planning, through the knowledge and influence within the relevant governing boards (ALMA, ESO, NSF, etc), but most importantly through the work and collaborations of the GTC scientific community in ALMA-related projects. Therefore, the GTC instrumentation and operations are already and will continue to be naturally responding well to synergies and exploitation of the ALMA science plans and products.

Another important upcoming facility in this bandpass is the Large Millimeter Telescope in Mexico, for which INAOE plays a leading role. LMT will provide an important complement to ALMA capabilities, both internal and external to the GTC partnership. Also, LMT shares a similar latitude, and thus sky coverage, with GTC. Potential synergies between this facility and GTC future instrumentation should be given appropriate weight in evaluating priorities.

d. Other space missions

In the coming years other space missions with participation from GTC partner countries/institutions, such as HERSCHEL and GAIA, will probably require GTC follow-up observations.

GAIA (scheduled to be launched in Dec. 2011) will provide unprecedented astrometric measurements for about one billion stars in our Galaxy and throughout the Local Group. GAIA also has photometric and high resolution spectroscopic capabilities. However, its high-resolution spectroscopy is limited in sensitivity and spectral range (847-874nm), being in practice only feasible for a small fraction of the sample for which high precision astrometry and photometry will be obtained. Therefore, follow up complementary observations with GTC call for a medium/high-resolution ($R\sim20000$) optical spectrograph with multiplexing capability. That will make possible to obtain radial velocities and perform abundance analyses for most of the stars contained in the sample observed by GAIA. Also an optical IFU capability in the GTC will permit spectroscopy of very dense regions observed with GAIA.

HERSCHEL (planned to be launched in 2008) is optimized from the far-infrared to sub-millimeter wavebands and, though complementary observations with GTC are expected for some studies, we do not foresee a clear specific call for a particular type of instrumentation. However, high angular and spectral resolution near-infrared spectroscopy with GTC may probably be needed for objects with molecules associated to circumstellar disks detected by HERSCHEL, which will be well served by current instrumentation.

WSO (World Space Observatory) is a space based UV-mission led by Russia, consisting of a 1.7-m telescope and two UV spectrographs (R= 55000 and R=1500-2500), as well as UV and optical imaging capabilities. Spain has strong participation in WSO, and therefore its community will have privileged access to the data and observing time. Therefore, WSO may constitute also an important source of targets for GTC, in particular taking into account that it is the only UV mission planned after HST.

II. Near-Future Instrumentation

In this section, we present analyses of the GTC instrumentation capabilities and priorities for the Near-Future term – meaning from the present moment to instruments which may begin coming on-line in 2013 and beyond. In Section II.A we present a description of our basic motivation and approach used for this analysis. In Section II.B we present specific recommendations derived from this approach, including specific instruments we recommend for study, and specific issues for which the GTC Project requested analyses on the UES and SIDE instruments. In Section II.C we present recommendation for GTC operations related to instrumentation capabilities. In Section II.D we present the timeline and rough budget estimate for these recommendations. Finally, in Section II.E we present a summary of the key recommendations for the Near-Future term.

A. Motivation/Approach

1. Workhorse instruments

GTC primarily serves a specific user community in Spain, Mexico, and at the University of Florida. This community is broad in its scientific interests and hence its instrumentation needs are also diverse. The GTC will fulfill an essential role for a large fraction of this community since it will provide prime large telescope access to the Northern skies. Because of these particular circumstances and to serve the community in the best possible way, GTC must achieve a good balance between hosting general-use workhorse instruments and instruments optimized for a specific capability driven by a very specific science goal. Instruments with a broad, and therefore less-specific, science case may appear less convincing in the absence of a “killer” application. However, such general-purpose instruments, if well-designed, are likely to attract a broad community of users and will find use in novel science programs unforeseen at the time of their conception. So, high quality work-horse instruments have long prospective competitive lives. Many future science programs – for instance those linked to space missions requiring ground-based complementary observations, or for target-of-opportunity observations – will need basic (but high-quality) optical and near-IR spectroscopic and imaging capability that GTC should provide.

Such workhorse capability should focus on:

- High-throughput optical and near-IR imaging, exploiting natural seeing and delivering the widest reasonably available field.
- High-throughput optical and near-IR medium-resolution spectroscopy, exploiting natural seeing and delivering the widest reasonably-available field and multiplex gain.

- Although it is still early for GTC to conceive routine AO operations, a near-IR high-spatial-resolution imager/spectrograph should be also considered a modern-day work-horse instrument.

Good examples of such high-quality general-purpose instrument are the XShooter optical and near-IR spectrograph that will be the first of the second-generation instruments on the VLT or the AAOmega VPH articulated spectrograph on the Anglo-Australian Telescope.

It is important to realize that highly-stable workhorse instruments become much more powerful through time, as the broad user community builds up a highly reliable set of calibrations, reduction packages, data bases and overall wide application experience to exploit the instrument capabilities to its ultimate limit. Ease-of-use and the ability to quickly obtain reduced and publishable data is very important for effective work-horse instruments.

For the reasons mentioned above GTC should not hold back on deploying general-purpose instruments even if there is no obvious “killer” application, or when similar capability is available at other telescopes, as long as such instruments are competitive.

2. Covering Parameter Space

Given the unique role that GTC plays within its user community, it will be important that GTC’s instrumentation suite covers the most essential instrument capabilities. The planned set of instruments actually already provides for a very good coverage of wavelengths and spectral resolutions. The diagram below crudely indicates for each instrument which area is covered in the resolution-versus-wavelength parameter space. Colored areas refer to approved instruments, while the grey outlines are for two proposed instruments. (Note that SIDE is a proposed multi-object fibre spectrograph, and UES a refurbished fibre-fed echelle spectrograph)

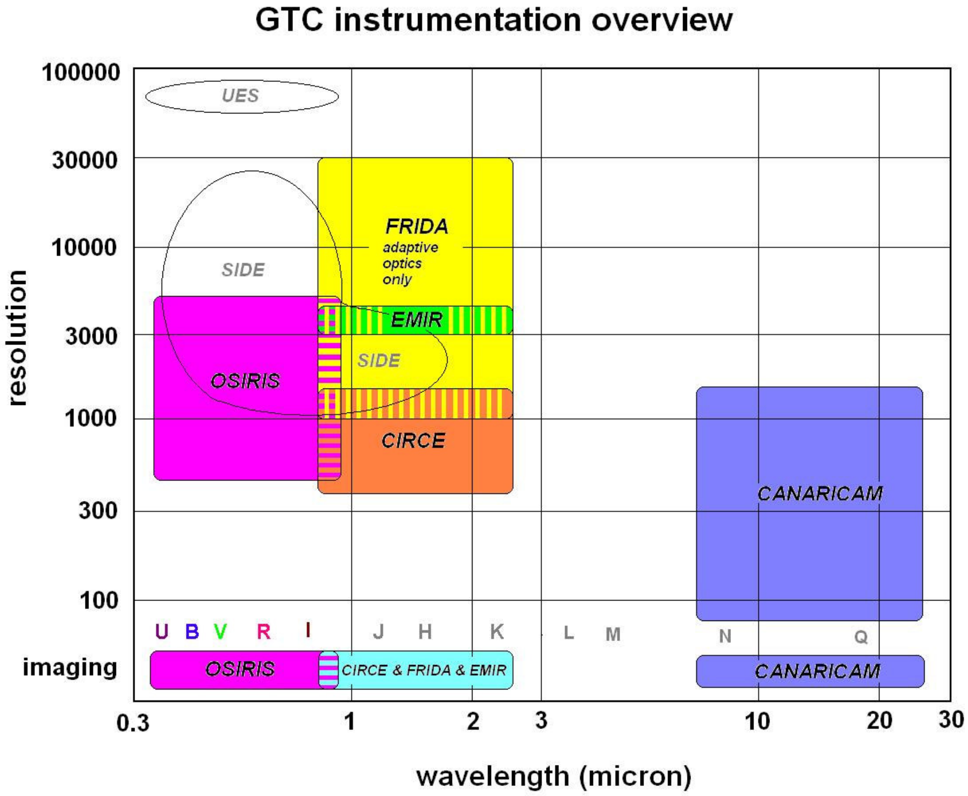

Figure 1 *– Parameter space for GTC instrumentation*

The diagram obviously simplifies reality and does not show full technical detail and capability of each instrument, such as multiplexing capability, field-of-view, polarimetric capability, or image quality and delivered Strehl ratio. However, it may serve as an overview and guide as to where specific overlap or gaps in basic capability lie.

From the above diagram we conclude that there are four areas in the approved instrumentation suite where capability is lacking: (i) medium-resolution optical spectroscopy, (ii) high-resolution optical spectroscopy, (iii) medium/high-resolution near-IR spectroscopy, (iv) medium/high-resolution mid-IR spectroscopy (though poor sensitivity may be a serious limiting factor here). We note that L and M-band imaging and spectroscopy can be covered by CanariCam, although these bands are not part of its main design drivers. Medium-resolution optical spectroscopy has already been identified by GTC as a key development area (see further discussion in section II.B below). Furthermore, for high-resolution optical spectroscopy, an attractive fast-track solution is offered by the deployment of an existing (but refurbished) instrument – UES – provided it will be competitive. We consider that another high priority for GTC to consider will be a medium-/high-resolution seeing-limited near-IR spectroscopic instrument. Close competitors of such instrument at other large telescopes are NIRSPEC on KECK-II and CRIRES on the VLT.

For future new instruments in general multiplexing capability is highly desirable and partly catered for already through planned instrumentation. In each case such capability needs to be justified through a detailed scientific, technical and budgetary analysis.

B. Specific Instruments Recommended for Study

In this section, we further describe the two primary instruments we have identified for study as near-future instruments for the GTC. As noted above, carrying out detailed studies of science drivers, technical capabilities, and science/technical/cost/risk trade studies for such instruments are all well beyond the scope of this report. Furthermore, such studies are best carried out by larger instrument teams drawn from the GTC community as a whole, so that the interests of the community are properly represented. Our purpose here is to provide the GTC Project Office and the GTC community with enough definition of the likely instrument parameters to allow the initiation of such in-depth studies. In Section II.B.1 we describe the medium-resolution optical spectrograph. In Section II.B.2, we describe the medium/high-resolution near-infrared spectrograph. In Section II.B.3, we address specific issues for the SIDE and UES instruments proposed for the GTC, as requested by the GTC Project Office.

1. Optical spectrograph at R>10,000

A mid-resolution optical spectrograph (R=10000-20000) has already been recommended by the SAC as the next instrument that should be developed by the GTC. We fully agree with this recommendation. This should be a workhorse, multi-purpose instrument aimed at giving support to a large number of projects. As stated above, it should be an instrument with significant multiplexing capability, not only to take advantage of large surveys, but also because in current research many results have been reached only after analyzing a large number of objects. Possible references (and competitors) would be FLAMES-GIRAFFE and MUSE at the VLT or WFMOS at Subaru. Note that at present there is no such an instrument operating in the northern hemisphere, and only GMOS, with limited resolution, would be a competitor in the blue (DEIMOS at Keck II is also a competitor in the red). The so-called “high-resolution” spectrograph included in the current SIDE proposal may be an adequate solution (although of course other approaches are also possible). The low resolution part of SIDE does not contribute to the merit function of GTC in terms of resolution, as this is already covered by OSIRIS and EMIR (although the proposed multiplexing capability of SIDE may be significantly larger – see Section II.B.3.a for further discussion).

2. NIR seeing-limited spectrograph at R>10,000

The region of R=10000-20000 in the near-infrared (NIR) seems to be already covered in Figure 1 by FRIDA, but this is an adaptive-optics instrument and its field of view is consequently limited (on the order of one to a few square-arcseconds). In the last decades, the effort in the NIR, both observational and theoretical, has been enormous and the same arguments that can be used for an optical mid-resolution spectrograph can be applied to the NIR range. The same kind of studies (kinematics, abundances, stellar and ISM properties, galactic structure, etc.) can be performed in the NIR, with the obvious advantages of the much lower extinction and the access to cool, red objects. A seeing-limited, NIR instrument with R~20000, multiplexing capability of a few to few x10 over a large patrol field of view, and broad wavelength coverage would thus be a very important workhorse instrument with large applicability. We recommend such an instrument, which has not been planned or proposed for GTC, nor is planned or available at any other 8- to 10-m telescope.

An instrument at much larger spectral resolution (R=150,000, NAHUAL) has been proposed. Such an instrument would be preferentially dedicated to high-precision radial velocity studies and could also be used for the identification of new spectral features (separating contributions blended at lower resolutions or revealing faint lines). Here again we have the same situation as in the optical with UES, though perhaps with a more focused, less-extended interest in the GTC community. Although here the competitiveness and the interest of the particular scientific case is clear, the higher cost and the more limited use as a general instrument require specific study to determine whether this instrument may also be of interest as a priority for GTC.

3. Other specific considerations

In this subsection, we consider two specific issues as requested by the GTC Project Office. Specifically, the GTC project office has asked us to consider whether or not the proposed SIDE and UES instruments, if they are NOT available on the GTC, would leave significant gaps which the GTC would need to fill at high priority. We first consider the proposed SIDE instrument and then the proposed UES upgrade.

a. SIDE

The mid-resolution optical spectroscopy (R=10000-20000) is another region clearly not covered presently by GTC (i.e., by one of the instruments in construction or already approved) but is a field of large interest for the GTC community, as it has already been recognized by the SAC, who recommended an instrument with these characteristics – see also section II.B.1. The higher-resolution portion of SIDE as currently proposed would seem to adequately fulfill this need for the GTC community. However, it is the understanding of this Working Group that the primary cost/resource drivers for the current SIDE proposal derive from the low-resolution optical/near-infrared portions of the SIDE spectrograph. These portions of the SIDE proposal do not have any positive impact on the merit criteria we have established here – on the contrary, they contribute to a substantial increase in risk and cost. Other groups/committees are currently being commissioned to review the SIDE proposal as a whole, and will presumably pay close attention to the issues of whether the scientific gains which may actually be realized by the lower-resolution portion of SIDE are sufficient to motivate these dominant cost/resource/risk drivers, especially given the existing multi-object spectroscopic capabilities provided by OSIRIS and EMIR on the GTC.

b. High-res optical (i.e. UES)

High resolution spectroscopy requires a large number of photons. Except for specific projects, only the largest telescopes at each moment can be really competitive. Therefore, high-resolution spectroscopy is one of the fields in which GTC will be very competitive due to its large collecting area. As it can be seen in Figure 1, this is a region of the instrumental parameter space not currently covered by GTC (neither in the optical nor in the NIR). In addition, in the northern hemisphere only HIRES is a competitor on a similarly-large telescope; in the South, UVES and Espresso will be serious competitors.

An advantage of optical high-resolution spectroscopy is that the data needed for full analysis (i.e. atomic line databases) are fairly complete and the physical processes involved are well understood (without meaning that we know everything). This allows us a good interpretation of the observations. However, high-resolution spectroscopy is a very specialized field. It is therefore important to explore whether there is sufficient interest in the community to which it is addressed. While this has to be done by consulting the GTC scientific community, we may identify a few fields in which optical high-resolution (R>30,000) spectroscopy can be of interest (without pretending to be complete).

- Abundances in the ISM at large and intermediate z ($L\alpha$ forest, Damped $L\alpha$ systems, quasars, starbursts and star forming galaxies) and in the Local Universe
- Stellar structure and atmospheres: pulsations, line asymmetries, abundances in slowly rotating stars or low density environments (chromospheres, super- and hypergiants), detection of weak lines
- High precision radial velocity studies in all kind of objects, and high-order moments of velocity distributions (e.g. anisotropy, tri-axiality, etc.) in unresolved stellar systems and galaxy nuclei.

These areas cannot be properly covered at lower resolution, even using high S/N ratios. There are groups in the GTC community working in topics related to all these areas. Therefore we recommend that the GTC Project Office commission a small study or working group to seriously explore interest in the GTC community and study the costs/benefits at issue. The UES proposal in particular should be seriously considered, because it may offer a relatively high benefit at low cost, but a study to confirm the competitiveness and interest of the specific proposal should be performed (including sensitivity, wavelength coverage, target multiplex, velocity precision/stability and science drivers).

C. Recommendations for GTC Operations Models

1. Queue-scheduled observing

a. Importance

An important advantage of the GTC operational model will be the use of queue scheduled observing. If implemented well, with due care to scheduling in accordance to scientific priority and environmental parameters (e.g. sky brightness, seeing, transparency) and with attention to quality control, queue scheduled observing could be an important factor in the overall scientific efficacy and success of the telescope. Queue scheduled observing is particularly relevant for observations that require special environmental circumstances, such as exceptionally good atmospheric turbulence conditions for adaptive optics observations or low water vapor conditions for mid-IR observations. But in addition to observations that have such special requirements, in general terms queue scheduled observing can drastically increase the success rate of the top tier of observing proposals because scheduling flexibility makes them less susceptible to statistical fluctuations of the weather.

Broadly speaking, in queue scheduled observing mode the observations that are carried out during some night are not simply conducted according to a pre-defined schedule, but rather depend on the scientific ranking and the match of the observing requirements to the actual environmental conditions and the instruments available at that time. Based on established statistical knowledge of the observing conditions one can predict the chance of success of a certain program and with high fidelity guarantee that a specific program will be successfully completed within a certain period of time. Hence the success of an observation is much less a matter of good fortune, such as is the case in classical observing mode. In this way top-ranked proposals will experience a very high (~100%) success rate providing that the queue is managed well.

An important added benefit of queue scheduled observing is that the prevailing environmental conditions can be exploited in a fashion that is more optimal than in classical visitor-observing mode. For instance, good seeing conditions can be used for the scientifically most important programs that indeed require good seeing, rather than that such favorable conditions are used for programs that don’t require it. Also, flexible scheduling during the night allows making optimal use of dark, Moon-less skies, even on nights when the Moon is in the sky only part of the night, thus increasing the amount of valuable dark time.

b. *Requirements*

Queue scheduled observing requires that observatory personnel carry out the observations for reasons of complexity of possible changes in instruments or observing modes, for the need to conduct quality control so that a good data product will be delivered, and to ensure that the queue is accurately managed. Although the cost to the observatory in terms of effort required will be relatively large, the potential payoff in more and better science being delivered will also be large.

Choosing queue scheduled observing mode as such does not directly influence GTC's instrumentation development plans, but instruments should be suitable for queue scheduled observing and facilitate fast deployment and returning to stand-by mode. GTC operation should be prepared to switch between instruments during the night. Ideally, observations should be carried out in an automated fashion directly from the phase-2 observing proposal. This requires that the telescope and instrument can be controlled from a central sequencer. With its various focal stations available on GTC, this telescope is in principle ideally suited for queue scheduled observing and hence for reaping its benefits.

2. Visitor or "PI" Instruments

a. *Importance*

GTC may well wish to position itself as a platform for the deployment of visiting instruments. With visiting instruments we refer broadly speaking to instruments that are not developed, funded, or owned by GTC and will typically not be integrated fully into the GTC infrastructure as common-user tools for the wider community. The key reasons for hosting visiting instruments are: (i) they allow fast-track execution of very specific scientific projects that require an optimized instrument matching that narrow science goal. The science is usually urgent and novel, and since the instrument developers have a very specific goal in mind the scientific return comes usually fast and is significant. (ii) major scientific developments are often based around novel measuring techniques or observing methods. If proven successful, such techniques could later be incorporated into common-user instruments.

For both abovementioned aspects the GTC will receive positive press and "brownie points" in the user community. But more importantly, it will attract users, ideas, and new resources for instrumentation development that would otherwise not be available.

b. *Requirements*

But there is a price to pay: hosting visiting instruments tends to be time consuming for the observatory. There are many interface issues to deal with, usually requiring adaptations to infrastructure hardware and software. It requires negotiation and preparation, freight and administration, and much on-the-spot intervention and creativity. If not properly managed, visiting instruments can significantly distract observatory personnel from the normal day-to-day routine.

If GTC wants to welcome visiting instruments it needs to agree rules-of-engagement covering issues such as data ownership, interface standards, instrument use by others, available foci, etcetera. Having such guidelines prepared will reduce unpleasant surprises.

D. Timeline/budget

In order to have the above-recommended instruments operational at the telescope by 2013, their definition and development should begin immediately. An optical mid-R spectrograph was approved and sought by GTC since late 2002, and since the higher-resolution portion of the SIDE instrument is already providing a conceptual design for such a capability, such instrument should then be constructed and commissioned by 2013 in principle. On the other hand, we are not aware of any proposal for the NIR medium-/high-resolution spectrograph, so GTC should launch this initiative by the end of 2008.

Although standard Instrument Definition Teams should be sufficient to define the instrument concepts, it is important before kickoff, to develop a set of general high-level requirements for both optical and near-infrared workhorse spectrographs with the input of the GTC scientific community. Since none of these instruments requires particularly novel developments, nor needs unproven technologies, they both can go through all design, building and commissioning phases by 2013, provided that the IDT and GTC community do not demand severe extra capabilities and over-complexity that may compromise their development or success.

For the same reasons – fast and secured delivery with no-need for extra complexity – the budget required for these missing capabilities should not be excessive. A very rough estimate of the price for each instrument (including personnel) would be approximately eight to ten million Euros.

We have not included the UES proposal here, in that we expect its cost to be relatively small if the GTC community decides to implement it. We also note that the estimated total cost of SIDE significantly exceeds the above estimate by many millions of Euros. However, we believe this cost difference is driven by the lower-resolution portions of SIDE, which do not address the highest priority needs we have identified here.

E. Summary of Near-Future (2013+) Recommendations

We present here a brief summary of the key points and recommendations of the analyses for the Near-Future term (i.e. capabilities that will be coming on-sky beginning around 2013):

- GTC should develop a medium-resolution (R ~ 10,000 - 30,000) multi-object optical spectrograph, as described above, for on-sky commissioning in 2013. The estimated total cost of this project is 8-10 million Euros (including manpower). We note that such an instrument has already been formally endorsed by the GTC SAC and various other governing bodies in the GTC community.
- GTC should develop a medium-resolution (R ~ 10,000 - 30,000) multi-object near-infrared spectrograph, as described above, for on-sky commissioning in 2013. The estimated total cost of this project is 8-10 million Euros (including manpower). This timeline would require the initiation of a feasibility study for such an instrument in 2008.
- Queue-scheduled observations will be critical to optimizing the scientific return of the GTC, and should be fully supported.
- Visitor or "PI" instruments provide an important contribution to the potential scientific flexibility and productivity of the GTC, and the GTC should develop clear guidelines for working with such instruments.
- The "high-resolution" portion of the proposed SIDE instrument would seem to fulfill the requirements for the medium-resolution optical spectrograph (as we define the terms here). The low-resolution and infrared portions of the SIDE instrument would not seem to contribute directly to the merit criteria we have established here.
- High-resolution optical spectroscopy is an important scientific niche which particularly benefits from the large collecting area of the GTC. GTC should commission a study as soon as possible to assess the suitability of the UES instrument for meeting the scientific needs of the GTC community in this area, as well as possible alternative plans for this capability.
- A well-defined funding (and monitoring) scheme, well-adapted to the schedule and milestones of these projects, is highly recommended to optimize resources and achieve the desired results on time. The specificity of these generally multi-national, multi-institutional projects may require optimization of the general structure under which they are developed.

III. Mid-Future Instrumentation

In this section, we present analyses of the GTC instrumentation capabilities and priorities for the Mid-Future term – meaning instruments which may begin coming on-line in 2018 and beyond. In Section III.A we present a description of high-priority adaptive optics options/capabilities for the GTC in the Mid-Future term. In Section III.B we present a description of other instrumentation priorities which may possibly arise in the Mid-Future term. In Section III.C we present the timeline and rough budget estimate for these recommendations. Finally, in Section III.D we present a summary of the key recommendations for the Mid-Future term. We note that this section has an obvious emphasis on adaptive optics instrumentation. As we show below, this emphasis arises naturally due to both the intrinsic significant advantage GTC possesses for near-diffraction-limited observations even compared to other large telescopes, and also the confluence of the technological and scientific horizons and the time lag of the GTCAO 1st-generation system compared to other large telescope adaptive optics systems.

A. Adaptive Optics Capabilities

1. Motivation

In assessing the competitive ability of the GTC in the modern era, perhaps the greatest "negative" factor for the observatory is that of timing/maturity – GTC is nearly the last of the 10-m-class telescopes, and the first such large telescopes (i.e. Keck) have been scientifically operational for more than 15 years. On the other hand, in diffraction-limited science cases, the observing time advantage provided by large telescopes scales not as D^2 (as for most seeing-limited cases), but in theory for sky background-dominated faint sources scales as D^4. The D^4 scaling provides a significantly larger advantage for the GTC in near-diffraction-limited science than in seeing-limited science – a relative 17% increase versus Keck and nearly x2.5 versus the 8-m telescopes for faint-source diffraction-limited targets[1]. This advantage is further enhanced by the fact that near-diffraction-limited instruments for large telescopes – mid-IR and adaptive optics (AO) assisted near-IR instruments – are still early in their life cycles. For this reason, even with the time lag of GTC compared to the other telescopes, CanariCam on the GTC should make an immediate scientific impact – it will provide 2.5x the speed and 25% higher angular resolution than its nearest competitors (T-ReCS and MICHELLE on Gemini, VIZIER on VLT). Thus, this scaling effectively breaks the "degeneracy" between 8-m-class and 10-m-class telescopes, placing the GTC and Keck telescopes in a class of their own, with significant performance advantages over 8-m-class telescopes for diffraction-limited science cases. For science cases that can take advantage of this

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[1] Note that the segmentation of the GTC, being quasi-filled-aperture in nature, does not have a major impact on the diffraction/sensitivity scaling for most scientific applications – the one possible exception being very-high-contrast imaging (i.e. Eikenberry, Shkedi, and Herter, 2003, SPIE, 4837, 776).

scaling, we can consider as the "competition" only Keck I and Keck II. Even for science cases where the target sizes exceed the diffraction limit of the GTC, but are still smaller than typical seeing conditions – for instance, many extra-galactic applications – the GTC will potentially provide significant competitive advantages over the 8-m-class telescopes beyond the usual D^2 scaling.

For reference, currently, the Keck telescopes' diffraction-limited capabilities include single-conjugate adaptive optics feeding several instruments:

- NIRC2 (a "workhorse" 1-5 μm imager and slit spectrograph)
- NIRSPEC (a single-slit medium- to high-resolution near-IR spectrograph)
- OSIRIS (a new, near-IR moderate-resolution integral field spectrograph)

The Keck system has received a significant boost from the addition of a Laser Guide Star (LGS) with OSIRIS, which increases the sky coverage from <1% to >80%. This has enabled vastly improved scientific breadth in adaptive optics observations – particularly in extra-galactic science (though also in Galactic cases as well). The number of corresponding AO-based scientific publications has more than doubled with Keck in the past year, and the expectation is that this trend will continue for some time as more scientists get the opportunity to use this recently-developed capability. The GTC is already moving along this path with GTCAO and FRIDA, which will together match the capabilities of the Keck system (assuming a prompt laser upgrade for GTCAO early in its life cycle).

With the deployment of GTCAO, the GTC project will have to invest in understanding the system and learn from it. This is not merely a technological matter of understanding a new instrument. The potentially complex interplay of the atmosphere, the telescope, the AO system, and the science instrument will likely pose a significant learning curve before full science benefits can be reaped. GTC must be prepared for this and engage the community in this challenging but rewarding endeavor. Future AO developments such as proposed in this section will have to build on the success of the GTCAO system.

2. Adaptive Optics Options

In the current era, there are many available new options for adaptive optics, as the field and its enabling technologies mature. Particular examples include wide-field near-diffraction-limited ("near-DL") approaches (i.e. Multi-Conjugate AO and Multi-Object AO), wide-field image sharpening (i.e. Ground-Layer AO), visible-wavelength AO, and high-contrast AO. While the Keck Next-Generation Adaptive Optics (NGAO) project is considering several of these options, it will likely only be able to pursue one or two of them. Thus, the GTC has the opportunity to take a leading role in some of the leading capabilities in a significant portion of the future adaptive optics parameter space. To better consider the alternatives, we briefly describe below four potential approaches to future adaptive optics with the GTC:

Ground-Layer AO (GLAO) – This approach to AO seeks to use image-sharpening correction to improve upon seeing-limited PSFs, providing FWHM ~0.3-arcsec over fields as large as tens of arcminutes on large telescopes. Scientifically speaking, this approach is as diverse and flexible as seeing-limited science, with the added advantages of ~x2 improved spatial resolution and ~x4 improved sensitivity (in terms of observing time for background-limited observations). GLAO systems are planned for Gemini-North and the VLT, using an array of imaging, multi-object spectroscopy, integral-field spectroscopy, and multiple deployable integral field unit ("multi-dIFU") spectroscopy instruments. However, because it is not diffraction-limited, GLAO only provides D^2 sensitivity enhancement of the GTC compared to other large telescopes (i.e. the same as for seeing-limited observation), forfeiting some of the potential advantages for the GTC. In addition, GLAO depends critically on the height of the turbulent ground layer at the telescope site, H, in that the solid angle of the GLAO-correctable field of view scales as $\sim 1/H^2$. On the other hand, GLAO is very scientifically diverse in its reach – the majority of seeing-limited scientific observations are possible (and improved) with GLAO.

High-contrast AO (HCAO) – As noted above, this approach may suffer the most from the segmented primary mirror of the GTC. While the total amount of light which is diffracted into "sidelobes" by the segmentation is small (~1%), it is large compared to the faint target intensities in high-contrast imaging. Thus, sidelobes of the brighter object can masquerade as, or even swamp, the primary PSF peak from the fainter targets. For this reason, the primary effort of the Keck AO community in high-contrast imaging – the Gemini Planet Imager (GPI), which is led by Lawrence Livermore National Laboratory and the University of California – is actually being implemented on the monolithic-mirror Gemini telescope.

Visible-light AO (VLAO) – This approach to AO seeks to extend near-diffraction-limited correction to the optical V-band (or shorter wavelengths) by using larger numbers and higher speeds of wavefront sensor pixels and deformable mirror actuators. This has all the usual advantages of observing in the most commonly-used (and in many senses, most scientifically sensitive/productive) bandpass in astronomy (as opposed to the less mature and sensitive observations typically available in the NIR or mid-infrared). However, VLAO is unproven and relies on dramatic (and as-yet unrealized) improvements in some of these technologies. For instance, the US National Science Foundation Roadmap Panel for Adaptive Optics recently (October 2007) concluded that VLAO is a high priority for significant national investment in necessary technology development simply in order to demonstrate its potential for scientific productivity.

Multi-Conjugate AO (MCAO) – MCAO is an approach to AO where (as its name implies) multiple deformable mirrors are optically-conjugated to different heights in the atmosphere corresponding to multiple turbulent layers. This approach (as opposed to the classical "Single Conjugate AO" or SCAO of most systems to-date) allows near-DL correction over much larger fields of view in the NIR band and (perhaps just as importantly) with stable/well-behaved point spread functions as a function of position within the corrected field. (Typical SCAO systems are notorious for producing PSFs which vary significantly across the field and with time, making accurate photometry or quantitative spectroscopy very difficult). This approach has been thoroughly simulated, and tested in laboratory environments, and over the year or two has seen several successful on-sky demonstrations with the MMT and VLT as a “proof of concept”. Most MCAO systems require multiple guide stars to tomographically probe the atmospheric turbulence above the telescope at any given instant and properly feed control signals to the deformable mirrors. Thus, current MCAO systems being developed either have very low sky coverage using multiple bright natural guide stars (i.e. MAD on VLT) or else will have reasonably high sky coverage using multiple laser guide stars (i.e. Canopus on Gemini) – though other approaches are being considered which could provide a balance between sky coverage and performance using only natural guide stars.

This approach provides an excellent combination of advantageous features for the GTC including:

- wide bandpass in a high-sensitivity wavelength range (~0.9-2.5 μm)
- correspondingly diverse/flexible scientific capabilities
- potential for D^4 scaling advantage for GTC.

With the latter, even though GTC will lag behind Gemini/VLT in implementation schedule, we can be uniquely powerful in resolution and sensitivity – an advantage further enhanced by the fact that both the Gemini/VLT systems will be operating in the Southern hemisphere. Also, given the great flexibility here, instrument choice can make further enhance uniqueness of GTC (see discussion below).

Based on the above, this committee focused on two of the options (MCAO and GLAO) for particular further study and analysis. We decided to drop HCAO from further consideration here because of the fundamental handicaps GTC’s segmented mirror may introduce to such a system’s performance. VLAO, while potentially very appealing, is currently perceived as a high-risk option. It will require significant technology development, as noted above, and as such even the approximate scientific performance (and thus potential benefits) of VLAO are currently very difficult to assess. Thus, while the GTC community should continue to monitor progress in VLAO technology, we award it a significantly lower priority for planning purposes.

In the subsections below, we present more detailed explorations of the MCAO and GLAO options in the context of future instrumentation for GTC.

3. MCAO & Potential Instruments

In the subsections below, we present a brief review of likely MCAO performance parameters on the GTC (III.A.3.a). We then provide a top-level description of drivers for potential MCAO instruments, along with recommendations for further study (III.A.3.b) including a multiple deployable IFU spectrograph. In subsection III.A.3.c, we describe the possible characteristics of such a spectrograph in more detail, along with two science programs to provide examples of the kinds of work that can be done with such a system.

a. Basic MCAO parameters

In Table 3 below, we present the expected typical full-system performance for a GTC MCAO system (based on the predicted performance of Canopus on Gemini). This assumes a laser guide star MCAO system with 3 fainter (R ~19 mag) natural guide stars for tip/tilt correction.

***Table 3** – MCAO expected system performance on GTC*

Parameter	Value	Comment
Image FWHM	Diffraction-limited (0.85-2.5 microns)	Full bandpass; true even for faint natural guide stars
Peak Strehl ratio	>60% (K) >40% (H) >20% (J) >3% (850nm)	At zenith Values decrease off-zenith (drop by ~x0.7 for K-band to ~x0.3 for J-band at 45-degree zenith angle)
Field of View (Strehl >0.5* peak value)	120-arcsec (H/K bands) 90-arcsec (J-band)	Gain in solid angle by ~x10-20 compared to SCAO systems
Field of View (stable PSF)	60x60-arcsec	Usable for precision photometry/spectroscopy
Sky Coverage	>70% (galactic latitude = 30°) ~15% (galactic pole)	

b. Science instrument possibilities

The MCAO system itself does not, of course, actually collect any scientific information – it simply provides corrected images for science instruments to analyze and record. Thus, the selection of science instruments for use with MCAO on the GTC will be a critical factor as well. "Workhorse" instruments for MCAO will fall into two broad categories: imaging and spectroscopy. Imaging with MCAO will be very scientifically useful and broad appeal (for instance, the first instrument for MCAO on both VLT and Gemini is an imager). On the other hand, in broadband imaging – even with MCAO correction – GTC will naturally suffer in terms of sensitivity (though not necessarily spatial resolution) in comparison to similar capabilities provided by space-based instruments such as JWST which may come on at this time. However, we note that the FRIDA instrument for GTCAO may be able to provide an imaging capability which is reasonably well-suited for MCAO on GTC, albeit subtending a slightly reduced field of view, with very little cost.

Meanwhile, spectroscopy – particularly integral field spectroscopy – can be a very powerful tool in conjunction with MCAO. This is especially true since such an instrument can have a true sensitivity boost over space-based instruments such as JWST in the NIR at moderate to high spectral resolutions. Since the primary benefit of MCAO over SCAO is the provision of a greatly-increased field of view, single-slit or even single-IFU spectrographs will be of little interest – again, the FRIDA instrument will already provide this capability with the 1st-generation GTCAO system, as does OSIRIS with Keck. However, multi-slit instruments will benefit from MCAO correction (for example, the FLAMINGOS-2 instrument on Gemini-South is designed to provide multi-slit spectroscopy in conjunction with the Canopus MCAO system). Even better yet would be a multi-deployable-IFU (multi-dIFU) instrument, providing multiplex gains combined with the spatial information/resolution at the diffraction limit enabled by MCAO.

Based on these considerations, we recommend studies of two potential instruments for MCAO with GTC. The first of these – a simple imager – could potentially be fulfilled by the current-generation FRIDA instrument, though a careful trade of the cost/benefit of a new MCAO-dedicated imager is definitely warranted. The second potential instrument – a multi-dIFU spectrograph – is described further below (Section III.B.3.c) along with some example science cases.

c. MCAO/Multi-dIFU Science Examples

The properties of the AO system and instrument needed will require detailed study well beyond the scope of this report. However, we can provide some approximate performance numbers based on studies and designs for MCAO systems on Gemini/VLT and IFU and multi-dIFU spectrographs for GTC (FRIDA) and TMT (IRMOS). These lead to the following parameters – primarily as an initial starting point for discussions

***Table 4** – MCAO/Multi-dIFU Basic Parameter Summary*

Parameter	**Value**	**Comment**
Wavelength	**0.8-2.5 µm**	Range of useful MCAO correction
Spectral resolution	**1,000-20,000**	Highest resolutions available only at finest pixel scales
Number of MOS probes	**~6**	Driven by balance between target density and cost/size
MOS patrol field	**2-arcmin diameter**	Range of useful MCAO correction
IFU field of view	**~2-arcsec diameter**	Smaller FOV for finer pixel scales
IFU field separation	**<1-arcsec min.**	Set by probe pickoff size
Slitlet widths	**25, 50, 100-milliarcseconds**	2-pixel widths matching 50% EED for various cases
Detector format	**2048x2048-pix**	HAWAII-2RG baseline
Instantaneous Wavelength Coverage	**Octave at low resolution; single atmospheric window at R~4,000**	
Sensitivity	**Sky background limited**	Detector noise becomes significant/limiting at higher resolutions

An instrument such as this has a very broad range of scientific applications, from galactic to extra-galactic. Detailed planning/description of these will be a critical task for future instrumentation, and also lies beyond the scope of this report. However, in order to give some idea of the range of science possible, we provide the following samples of scientific uses for an instrument with the properties described above.

i. Physics of the Bulge/Black-Hole Correlation in the Local Universe

Recent investigations have shown a remarkable correlation between the total mass (or velocity dispersion) of galactic bulges and the mass of the black holes which lay at the centers of these galaxies. Understanding this correlation is one of the key questions in the framework of galaxy formation and evolution. Little is yet known about the physical processes which lead to this relationship, but central ideas focus on gas transfer into and out of the central regions of galaxies (where the gravitational potential is the strongest), and the relationship of this gas flow to star formation. Basic unanswered questions are how black holes affect the star formation in galactic cores and how, in turn, star formation affects black hole growth. Galaxy mergers may play an important role in building up bulges and driving the growth of black holes early in their formation history. Thus, the star formation history within the inner parts of galaxies is thought to be a key to answering these questions, and can be probed through detailed abundance patterns in the oldest stars. These abundances carry elemental imprints from the earliest generations of stars. Importantly, GTC with an MCAO system and a multi-dIFU spectrograph can provide spatially-resolved spectra of individual stars in nearby galaxies. R=20,000 spectra in the H and K bands provide detailed abundance distributions of key elements, such as C, N O, Fe and many others, in red giant and supergiant stars. The alpha element ratios (abundances of Mg, Ti, Si, Ca compared to Fe) depend on the mass function of earlier generations of stars that have enriched the gas from which the observed stars have formed (Wheeler, Sneden & Truran 1989). The imprint of the earliest stars to form in the galaxy can thus be found. With the instrument/AO parameters presented above, GTC will be able to tackle observations such as this (and many other science cases relying on NIR spectroscopy of point-like targets in moderately dense regions) with unique power and sensitivity, realizing the full potential of its D^4 advantage.

ii. Galaxy properties at the epoch of peak star-formation (z ~1-3)

One of the flagship science drivers for current and future generation telescopes – including JWST, TMT, E-ELT, etc. – is the detailed study of galaxies in the era of peak star formation at redshifts $1<z<6$. This redshift range encompasses no more than the first ~30% of the age of the Universe, but may account for as much as ~70% of its total star formation, heavy element production, and black hole accretion (Madau & Shull 1996; Pei & Fall 1995; Pei et al. 1999). This is also widely believed to be a critical epoch in the emergence of massive galaxies. The redshift range $1<z<6$ has consequently become the focus of future major galaxy surveys aimed at understanding the physical processes that determine the formation of galaxies and their evolution into today's galaxy population (for instance, GOYA with GTC and OTELO with OSIRIS, among others). However, the empirical understanding of galaxy formation ultimately requires detailed mapping of the physical properties, including kinematics, metallicity, age, star formation rate, and extinction, *as a function of spatial position within each galaxy*. For each galaxy, observations with MCAO and a multi-dIFU spectrograph as described above will provide:

- *Star Formation Rate (SFR) maps:* via measurements of the H_α and [OII]3727 emission lines (Kennicut 1989).
- *Metallicity maps:* via measurements of the R_{23} ratio ([OII]3727 + [OIII]5007)/H_α (Edmuds & Pagel 1984), and [NII]/H_α ratio (Storchi-Bergman et al. 1994).
- *Extinction maps:* via the Balmer decrement (H_β/H_α) (Calzetti et al. 1994).
- *Dynamical masses:* via measurements of the internal velocity field, instead of a rotation curve or velocity widths (Vogt et al. 1997; Guzman et al. 1997; Erb et al. 2004).
- *Gas kinematics:* via emission line profiles and kinematical subcomponents to quantify the outflow/inflow of gas from/onto galaxies (Marlowe et al. 1994).

4. GLAO & Potential Instruments

In the subsections below, we present a brief review of GLAO likely performance and issues on the GTC (III.A.4.a). We then provide a top-level description of drivers for potential GLAO instruments, along with recommendations for further study (III.A.4.b). In subsection III.A.4.c, we summarize the kinds of work that can be done with such a system.

a. Basic approach/parameters

Ground-Layer Adaptive Optics (GLAO) aims to correct wavefront distortion due to ground layer turbulence only, while essentially ignoring turbulence at greater heights. The resulting AO correction does not typically produce near-diffraction-limited images, but simply achieves “image-sharpening” compared to seeing-limited PSFs. Rather than taking ~0.5-arcsec FWHM and turning it into ~50-mas FWHM diffraction-limited PSFs, GLAO would instead yield ~0.3-arcsec FWHM PSFs. However, the field over which the correction is achieved is relatively large compared to MCAO (for instance), even up to 10-arcminute diameters. For science cases where field-of-view is important rather than diffraction-limited angular resolution, GLAO can be an attractive option. An example is that of integral-field spectroscopy over moderately wide fields where in-slit energy is the defining factor for observing efficiency, or imaging and spectroscopy at very short near-IR and optical wavelengths where, as discussed for VLAO above, very high fidelity AO is not achievable with current day technology, but where GLAO can deliver much improved image sharpness with a comparatively stable PSF over the field.

GLAO has some technological advantages that might be of interest specifically to GTC. In particular, since only ground-layer turbulence is corrected only one deformable mirror is required. Moreover, in principle cheap, commercial laser technology can be used for (multiple) Rayleigh beacons, as has been demonstrated at the MMT. Furthermore, as noted earlier, the solid angle size of the correctable field of view for GLAO varies inversely as the square of the scale height of this ground layer. Since GLAO does not produce diffraction-limited images, GTC only has a D^2 advantage compared to other telescopes. Recent measurements at Mauna Kea indicate turbulent scale heights as low as <300m, so this parameter needs to be similar (<400m) for GTC to maintain a competitive advantage over the Gemini-North telescope and its GLAO system. Thus, in order to properly assess the utility of GLAO for GTC, it will be critical to obtain high-resolution (<100-m) measurements of the ground layer turbulence structure at the GTC site.

b. Science instruments for GLAO

i. Possible use of existing instruments

One potentially very attractive option for science instrumentation with GLAO is the use of already-existent GTC instrumentation, at little/no additional cost beyond the GLAO system itself. As noted several times, GLAO essentially enables the same observations as in the seeing limit, but with slightly sharper PSFs (as opposed to other AO approaches which produce much tighter near-diffraction-limited PSFs over a much more limited field of view), and therefore improved sensitivity. Thus, to first order, any seeing-limited instrument for GTC would also serve for GLAO observations, as long as the pixel scale is small enough to properly sample the GLAO-delivered PSFs. If we assume that GLAO will deliver ~0.2-arcsec and larger FWHM under good observing conditions in the NIR and ~0.3-arcsec and larger FWHM in the optical, then instruments with pixel scales of ~0.10-arcsec (NIR) and ~0.15-arcsec (optical) will suffice. Thus, both CIRCE (0.10-arcsec/pixel) for the NIR and OSIRIS (0.125-arcsec/pixel) for the optical should be directly compatible with a GLAO system. Furthermore, OSIRIS can also provide multi-object spectroscopic and tunable-filter imaging capabilities for GLAO. It is possible that with appropriate optics schemes, EMIR could also be exploited with GLAO to provide multi-object NIR spectroscopic capabilities.

Thus, we can at least imagine that a very powerful instrumentation suite for GLAO could be provided at low cost from existing GTC instrumentation. The primary drawback of this approach is that it may not be able to take full advantage of the corrected GLAO field-of-view. And, as noted above, without taking that advantage, GTC runs the risk of losing the competitive edge provided by its superior aperture. In short, if either the GLAO-correctable field or the instrumental field of view is significantly smaller than ~8-arcmin diameter, GTC risks being at a sensitivity disadvantage compared to the Gemini-North 8-meter with a ~10-arcmin GLAO-corrected FOV. Thus, we can see that while the existing GTC instrumentation can certainly provide some initial benefit from GLAO implementation on GTC, to seek full advantage we would need instruments specially developed for GLAO.

ii. Possible future instruments

The range of optical/NIR instruments suitable for use with GLAO is as broad and diverse as those which can be considered for seeing-limited observations – from imagers to spectrographs, from polarimeters to multi-dIFU spectrographs, and so on. The critical features of any such instruments will be suitable pixel scales (i.e. ~0.10-0.15-arcsec/pixel) and efficient use of a full GLAO-corrected field of view of ~10-arcminute diameter. Logical high priority instruments could include optical/NIR imagers covering the GLAO full field, multi-object slit spectrographs, and/or multi-dIFU spectrographs in the optical/NIR. We mention here as an example the development of MUSE on the VLT, which will exploit massive integral-field spectroscopic multiplexing capability in the optical over a 1-arcminute field at a resolution of 0.2 arcsec.

Selecting among these options will of course depend on the expected GLAO PSF FWHM, FOV, etc. in the context of science drivers developed by the community, as well as trades of cost/benefit in light of the possibility of using existing GTC instruments in a (potentially) more limited manner.

c. *Science cases for GLAO*

As stated above, virtually any science case for seeing-limited observations which would benefit from sharper image PSFs would improve via the use of GLAO correction. One example would be spectroscopic studies of high-z galaxy populations. As a consequence of the relatively low number density of high-z galaxies, these studies require multi-object (or multi-IFU) observations over a large (patrol) field of view to take full advantage of the multiplexing gain. An improvement in the image quality implies a direct gain in sensitivity, which translates to moving down along the luminosity function and/or towards larger redshifts. Other examples would include studies requiring near infrared imaging of nearby galaxies (including, for instance, monitoring for SN searches), stellar population studies (imaging or spectroscopic) in crowded fields in the Galaxy and nearby galaxies (i.e. center of M31 and NGC 604 in M33), and many, many others.

B. Other Instruments/Capabilities

As described above, GTC is expected to have good and complete coverage of the instrumental parameter space for the optical to mid-IR by 2013, and we just mentioned above several relevant niches we think GTC should concentrate on by 2018 and beyond. It is then difficult to recommend further very specific instruments or capabilities for GTC for this Mid-Term era. Nevertheless, GTC should be quite aware of scientific and technology advances over the next 5 years, since these will lead to new and unique science programs which in turn motivate exciting new instrumentation. Among areas discussed by this Working Group as meriting special attention are:

1. Multiplexing. In the near future, it will become more common, possible and affordable to conceive instruments, groups of instruments and/or detectors for higher-multiplex observations (doing more than one thing at a time, like simultaneously covering different energy regimes, resolutions, observing modes, etc).
2. Quasi-simultaneous multi-mode. Similar to multiplexing, but not quite the same, is the potential to increase the ability to switch as quickly as possible between observing capabilities, to allow for an almost simultaneous measurement of several properties of a given object (e.g. imaging, spectroscopy, polarimetry, etc) as well as for a fast and proper response to observe relevant targets of opportunity.
3. Follow up of many other technical advances is of relevance too (fiber optics, lucky imaging, micro remote controlled mechanisms, special optical devices and detectors, micro/macro optics, coatings, etc.)
4. Changes in scientific focus. It is common that new findings and developments give known techniques or scientific areas new impulses. Radial velocity or transit studies for planet findings may be cited as a recent example. A possible

future field, among others, might be the study of magnetic fields through polarimetric measurements.

It is clear that GTC needs to be ready to jump on these yet-unknown opportunities. One possibility is that GTC prepares a specific fund for this, but it will be difficult to properly plan and quantify it. More realistically and practical for GTC is to define an aggressive program to attract visitor-type instruments, developed by groups and funds beyond the GTC observatory itself, to be the first to attract these first-of-class instruments.

C. Timeline/budget

In order to have the above-recommended instruments/capabilities operational at the telescope by 2018, their definition and development should begin very soon. Timing-wise, the earliest order of business will be a site characterization study with high altitude-resolution to determine the likely performance of GLAO at the GTC site. This study should be initiated as early as possible in 2009 and strive for completion by early 2010. Beginning in 2010, the GTC will need to initiate feasibility studies for both MCAO and GLAO possibilities for the GTC. These studies should include AO system and performance modeling, science cases, instruments (including performance and priorities), and cost/risk analyses. In the year 2011, the selected system(s) should begin conceptual design studies to be completed in 2012. Full design phase will need to begin in 2013 in order to have the first of the Mid-Future instruments on-sky by the stated goal date of 2018.

At this early juncture, it is extremely difficult to provide any more than rough order-of-magnitude cost estimates for the instruments/capabilities we have identified above. However, we estimate that the cost of the MCAO system may be ~8-10 million Euros (excluding backend scientific instruments), plus an additional cost of ~3 million Euros for a laser guide star system. A multi-dIFU spectrograph would have an estimated cost of approximately 13-16 million Euros (assuming 6 IFU/spectrographs at an average cost of 2-2.5 million Euros each and about 1 million Euros for a deployable pickoff interface). we estimate that the cost of the GLAO system may be ~6-8 million Euros (excluding backend scientific instruments), based on the Gemini GLAO feasibility study.

D. Summary of Mid-Future (2018+) Recommendations

We present here a brief summary of the key points and recommendations of the analyses for the Mid-Future term (i.e. capabilities that will be coming on-sky beginning around 2018):

- GTC should promote the development of science cases from the community and initiate feasibility studies for Multi-Conjugate Adaptive Optics capabilities, and related instrumentation capabilities, as described above. In order for these capabilities to come on-sky near 2018, feasibility studies should begin no later than early 2010.
- GTC should promote the development of science cases from the community and initiate feasibility studies for Ground Layer Adaptive Optics capabilities, and related instrumentation capabilities, as described above. In order for these capabilities to come on-sky near 2018, feasibility studies should begin no later than early 2010. Because GLAO performance is closely tied to the currently-unknown ground layer turbulence scale height at ORM, GTC should commission a study to provide high-resolution measurements of the ground layer properties in 2009.
- GTC should expect to develop additional instrumentation capabilities over this term. The details of the critical scientific performance characteristics of such instruments will emerge over the next few years in terms of both scientific and technological advances, and we have described some of the most likely focus areas above.

IV. Far Future (2023+)

Far future (2023+) GTC instrumentation will be determined by scientific and technological advances over the next 10-15 years. This is of course largely unknown. At that time JWST and ALMA are expected to be mature facilities, and giant ground based telescopes like E-ELT and TMT should already have been in operation for a number of years. These facilities are expected to change science's course and priorities, making fundamental breakthroughs in several fields.

While the prediction of science (and required instrumentation needs) at these long temporal scales is a very uncertain exercise, we have identify the following technological areas for which the GTC community should monitor progress closely.

- **Visible Light AO**: This seems a natural extension of current and mid-term planned AO developments for the next decade or so, in any case. Judging from developments at other large telescopes and the important technological advances that are under way, we do foresee that adaptive optics will continue to grow in importance for future novel astronomical instrumentation. GTC should therefore keep abreast with these developments.

- **Detector technologies**: Detectors (from naked eye to modern devices) have guided the progress of astronomy in the past and, they will likely guide its future as well. Although developments in this broad field are to some extent unpredictable, and involve a community much larger that the astronomical one, the GTC project should be ready to evaluate the potential of the different alternatives that may arise.

Further revisions of the present document (which we suggest to be carried out with a recurrence period no larger than five years, or so) will allow the GTC community to update and specify the areas for future developments in the 2023+ epoch.

In any case, and despite of all the uncertainty predicting future, we can just suggest approaches to take full advantage of an evolving scientific and technological environment. Readiness to consider new instrument concepts and technologies, strong involvement in the decision-making process of the community to which GTC ultimately serves, and a clear competitive scheme in the selection processes are all key elements to guarantee a successful future for GTC instrumentation.